Alexis

DM Predictions from the LHC

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Corpus Cristi, 05/2019

1. Introduction & Models

2. Results in SUSY GUT models

3. Results in the pMSSM11

4. Results in non-SUSY models

5. Conclusions

1. Introduction & Models

GUT based models:

1.) CMSSM: m_0, $m_{1/2}$, A_0, $\tan\beta$, $\text{sign}\,\mu$

2.) NUHM1: CMSSM + 1 scalar mass parameter
m_0, $m_{1/2}$, A_0, $\tan\beta$, $\text{sign}\,\mu$ and M_A

3.) NUHM2: CMSSM + 2 scalar mass parameters
m_0, $m_{1/2}$, A_0, $\tan\beta$, μ and M_A

4.) SU(5): CMSSM + 3 scalar mass parameters
m_5, m_{10}, $m_{1/2}$, A_0, $\tan\beta$, m_{H_u}, m_{H_d}

5.) mAMSB: different mechanism for SUSY breaking
$m_{3/2}, m_0, \tan\beta, \text{sign}(\mu)$

6.) sub-GUT: CMSSM, but unification at lower scale
m_0, $m_{1/2}$, A_0, $\tan\beta$, $\text{sign}\,\mu$ and M_{in}

7.) ...

$\Rightarrow$ wide variety of models covered!

Problem: We cannot be sure about the SUSY-breaking mechanism

$\Rightarrow$ it is possible that with the CMSSM, NUHM, SU(5), mAMSB, sub-GUT
we missed the “correct” mechanism

$\Rightarrow$ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches

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tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the "general MSSM"

$\Rightarrow$ 11 parameters are manageable $\Rightarrow$ pMSSM11

– squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$, $m_{\tilde{q}_3}$
– slepton mass parameter(s): $m_{\tilde{l}}$, $m_{\tilde{\tau}}$
– gaugino masses: M_1, M_2, M_3
– trilinear coupling: A
– Higgs sector parameters: M_A, $\tan\beta$
– Higgs mixing paramter: μ

What if we still did not get it right?

- low-energy model different?
- richer SUSY structure?
- no SUSY model? $\Rightarrow$ not really realistic!

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Lagrangian according to LHC-DM-WG recommendation:

The Lagrangians

- We consider DMSMs with a spin-1 (Y_1) s-channel mediator.
- The dark matter candidate is a Dirac fermion (X_D).
- We use the model files provided by the DMSIMP package for our implementation.

Spin-1 mediator

- Interaction Lagrangian mediator-DM
  $\mathcal{L}_{X_D}^{Y_1} = \bar{X}_D \gamma_\mu \left(g^V_{X_D} + g^A_{X_D} \gamma_5 \right) X_D Y_1^\mu$.
- Interaction Lagrangian mediator-quarks
  $$\mathcal{L}_{quarks}^{Y_1} = \sum_{i,j} \left[\bar{d}_i \gamma_\mu \left(g^V_{d_{i,j}} + g^A_{d_{i,j}} \gamma_5 \right) d_j + \bar{u}_i \gamma_\mu \left(g^V_{u_{i,j}} + g^A_{u_{i,j}} \gamma_5 \right) u_j \right] Y_1^\mu$$
- Interaction Lagrangian mediator-leptons
  $$\mathcal{L}_{leptons}^{Y_1} = \sum_{i,j} \left[\bar{l}_i \gamma_\mu \left(g^V_{l_{i,j}} + g^A_{l_{i,j}} \gamma_5 \right) l_j \right] Y_1^\mu$$

Scenarios

- Leptophobic, $g^V_{l_{i,j}} = g^A_{l_{i,j}} = 0$ (no constraints from dilepton searches).
- Flavor diagonal, $g^{V/A}_{u/d_{i,j}} = 0$ if $i \neq j$.
- Flavor blind, $g^{V/A}_{u_{i,j}} = g^{V/A}_{d_{i,j}}$.

1. $g^V_{X_D} \equiv g_{DM}$ $\quad g^A_{X_D} = 0$
   $g^V_{u/d} \equiv g_{SM}$ $\quad g^A_{u/d} = 0$,
   pure vector.
2. $g^V_{X_D} = 0$ $\quad g^A_{X_D} \equiv g_{DM}$
   $g^V_{u/d} = 0$ $\quad g^A_{u/d} = g_{SM}$,
   pure axial-vector.

[*taken from E. Bagnaschi*]

Our tool: **Mastercode**

⇒ collaborative effort of theorists and experimentalists

[Bagnaschi, Borsato, Buchmüller, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, Hahn, SH, Isidori, Lucio, Martinez Santos, Olive, Trifa, Sakurai, Weiglein]

Über-code for the combination of different tools:

- Über-code original in Fortran, now re-written in C++
- tools are included as subroutines
- compatibility ensured by collaboration of authors of “MasterCode” and authors of “sub tools” /SLHA(2)
- sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

Data we have:

- Higgs boson mass/couplings/... (LHC) $\Rightarrow$ FeynHiggs

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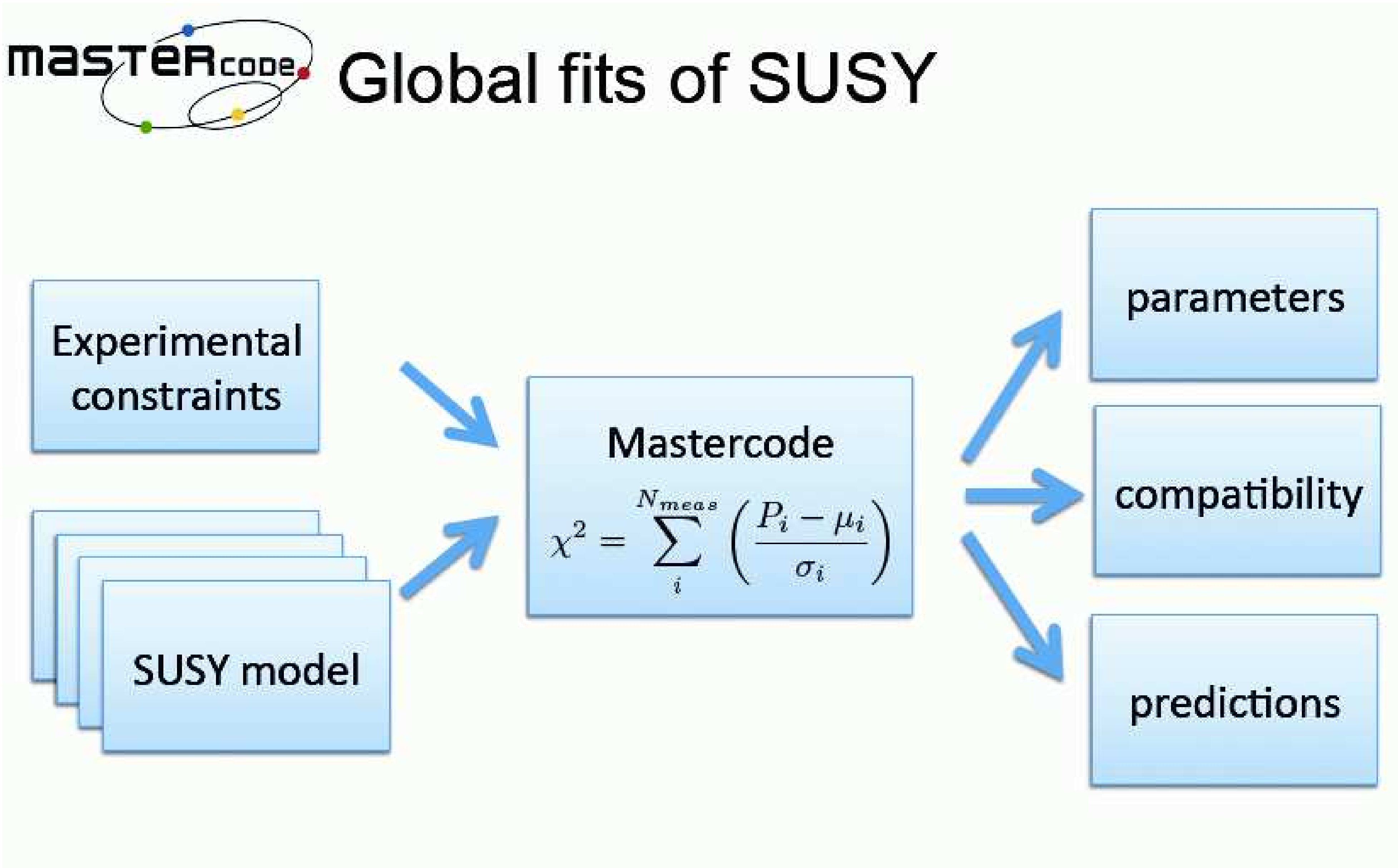
– electroweak precision data $\Rightarrow$ FeynWZ, FeynHiggs

– flavor data $\Rightarrow$ SuperIso, SuFla

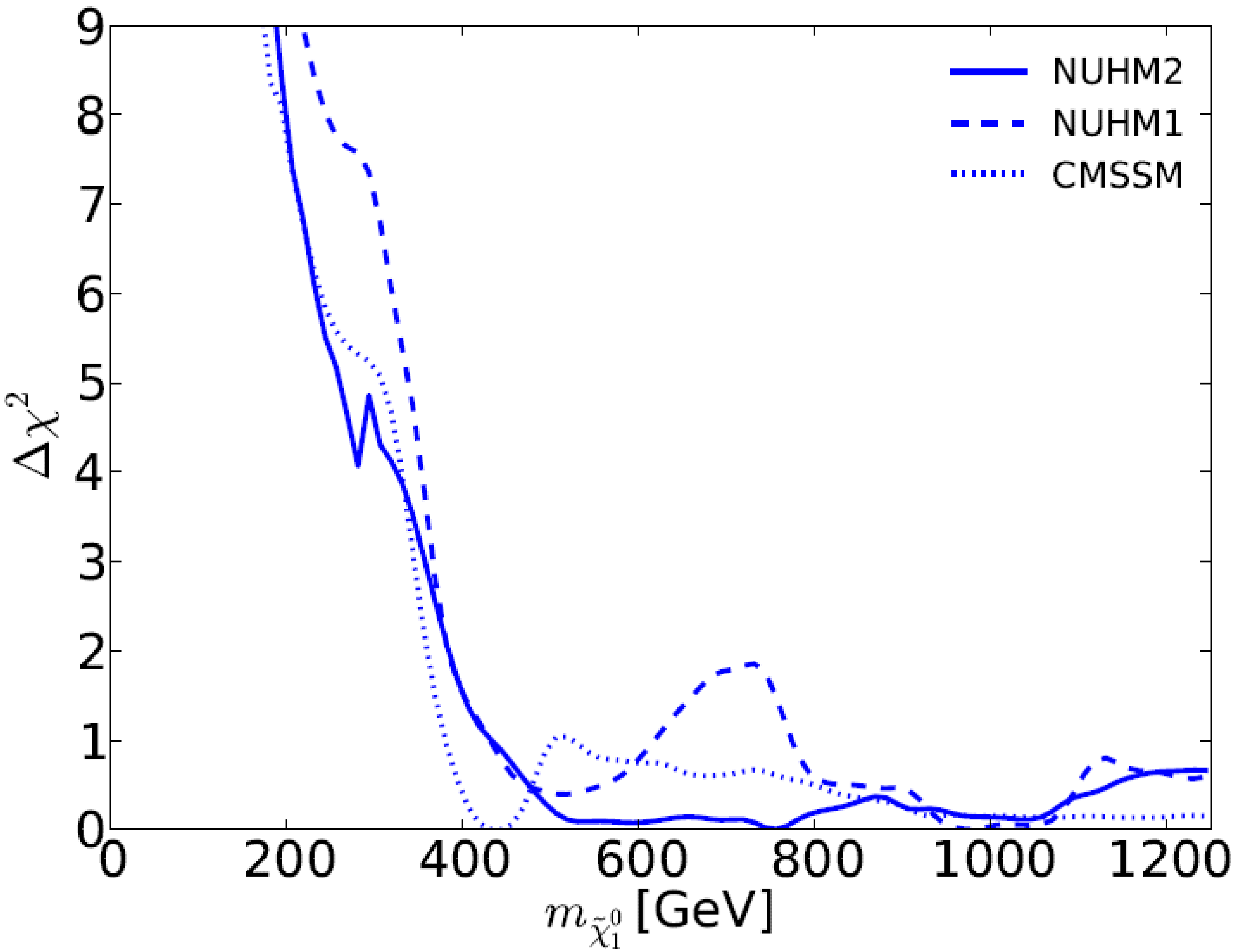
– astrophysical data (DM properties) $\Rightarrow$ MicrOMEGAs, SSARD

The χ^2 evaluation:



[2014]

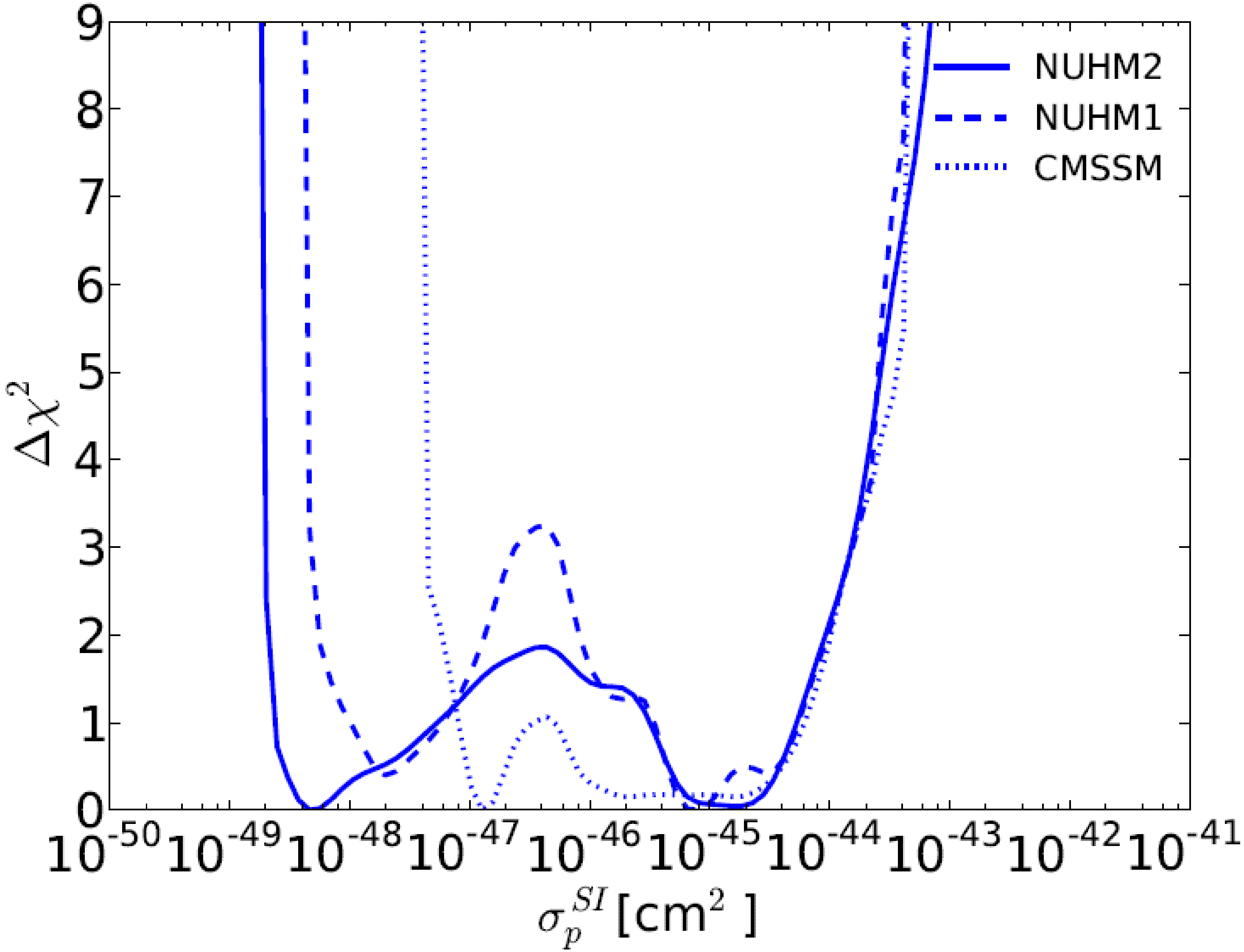
Results in the CMSSM, NUHM1, NUHM2



$\Rightarrow$ only very large values are favored

σ_p^{SI} incl. 20/fb of LHC data

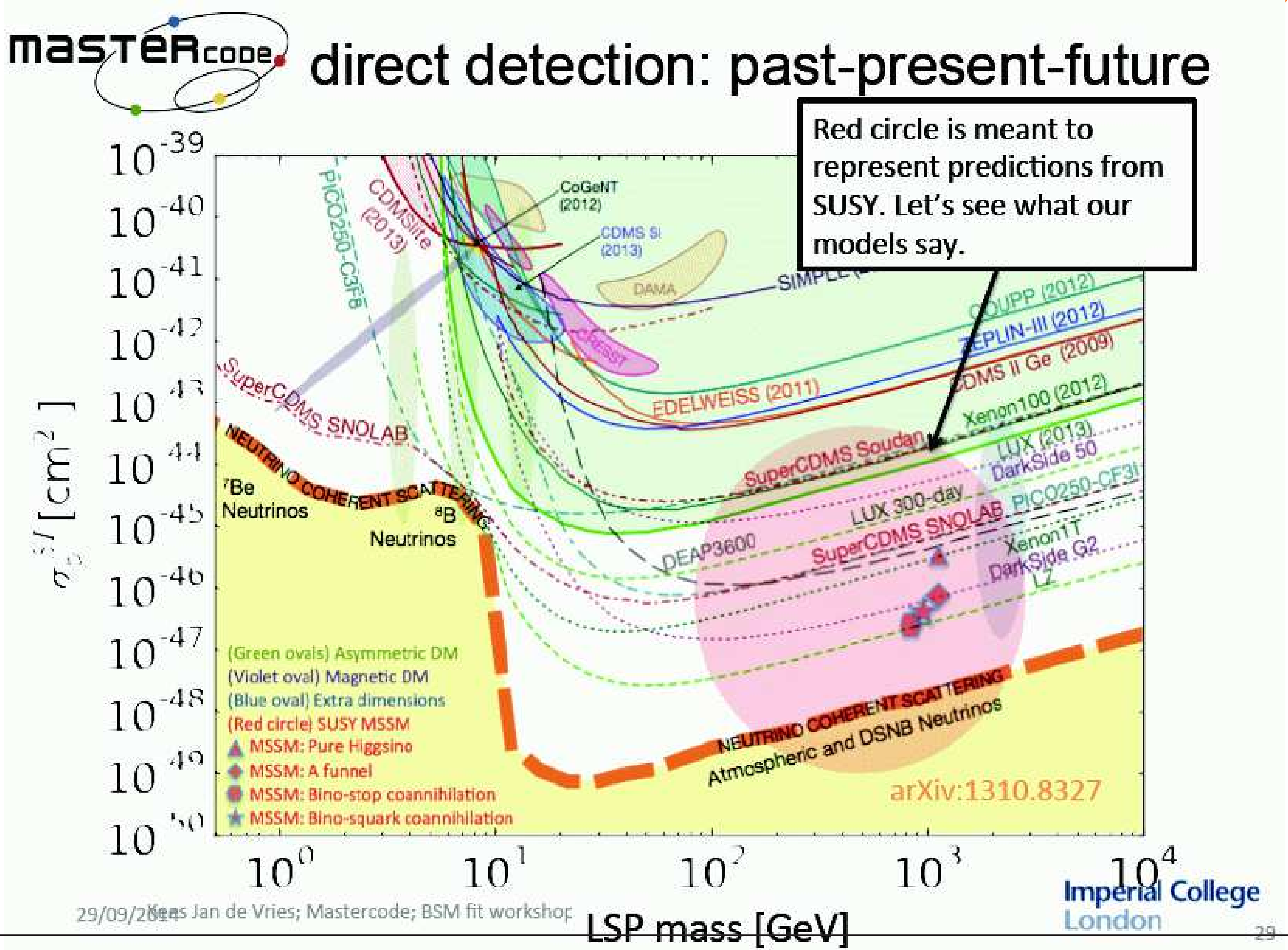
[2014]



$\Rightarrow$ only very small values are favored

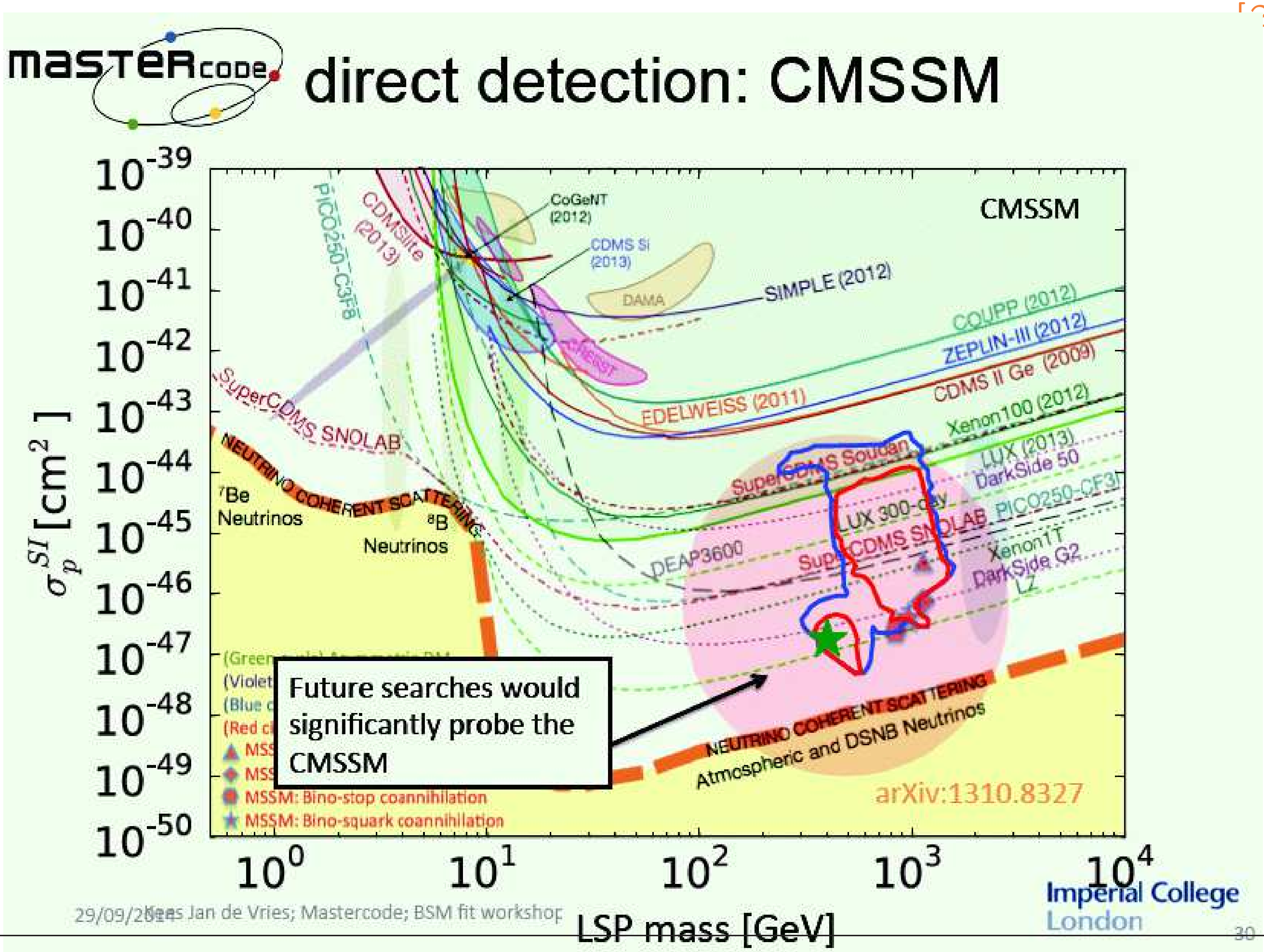
MSSM DM prediction

[2014]



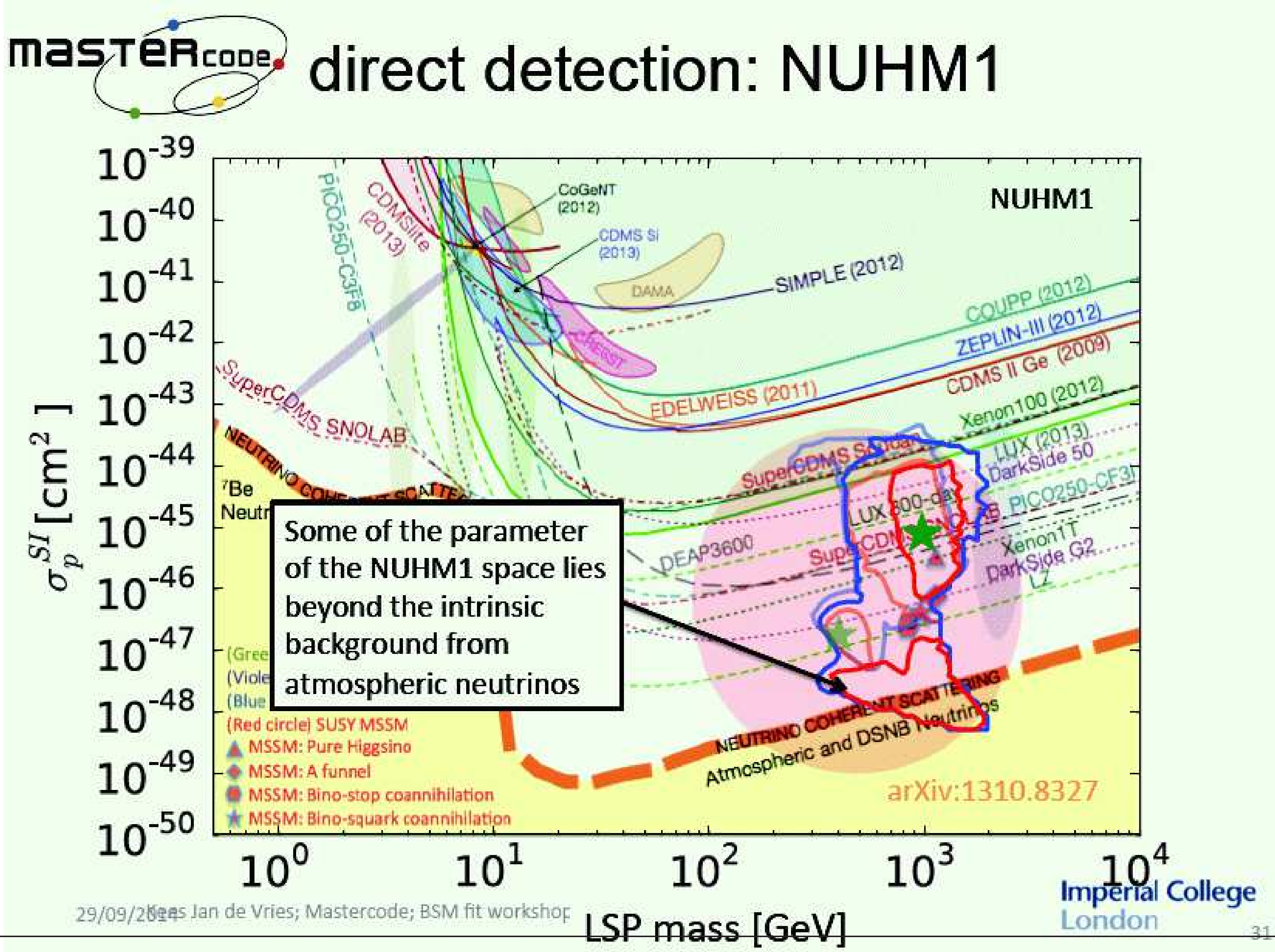
MSSM DM prediction

[2014]

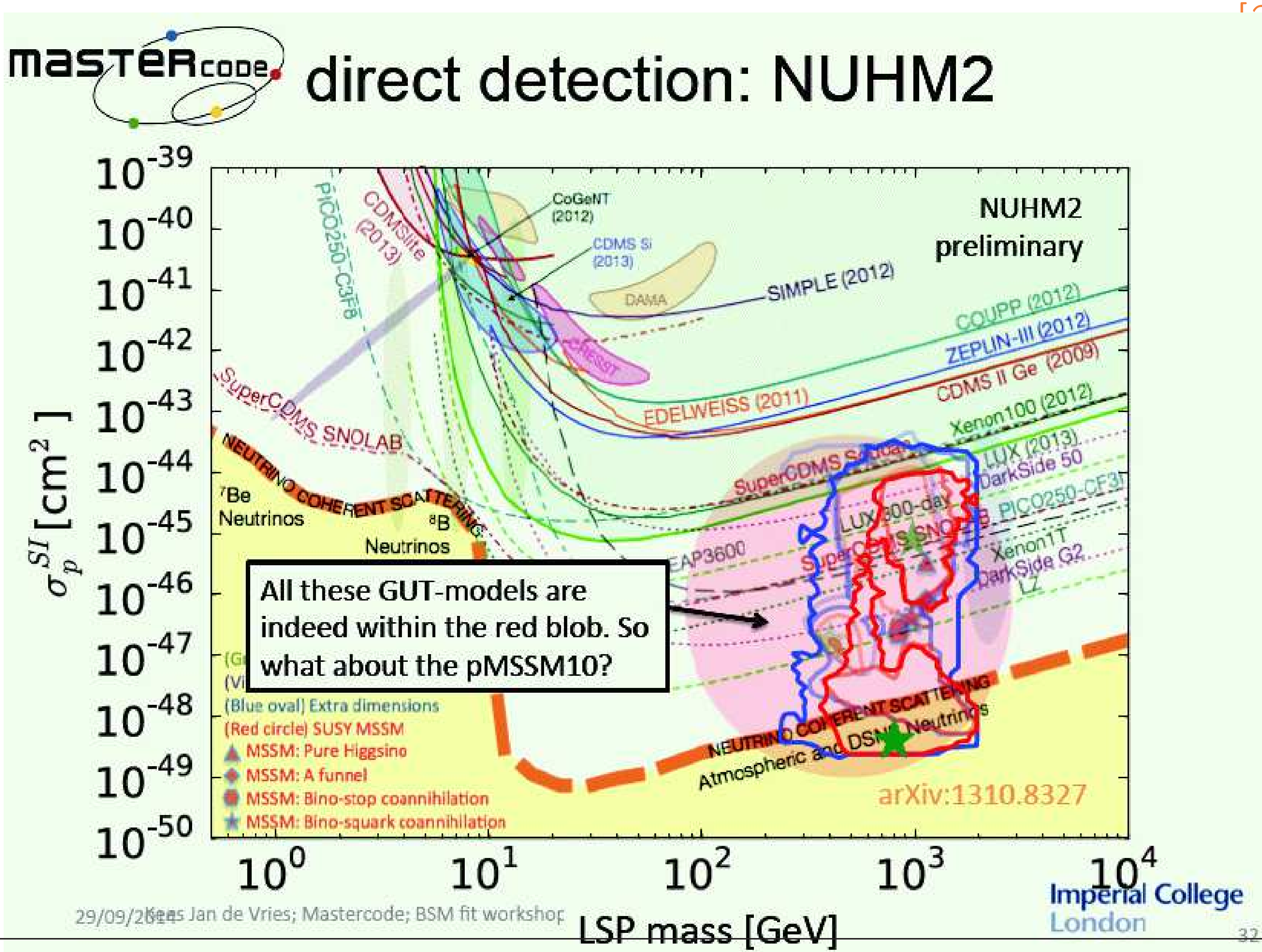


MSSM DM prediction

[?2014]



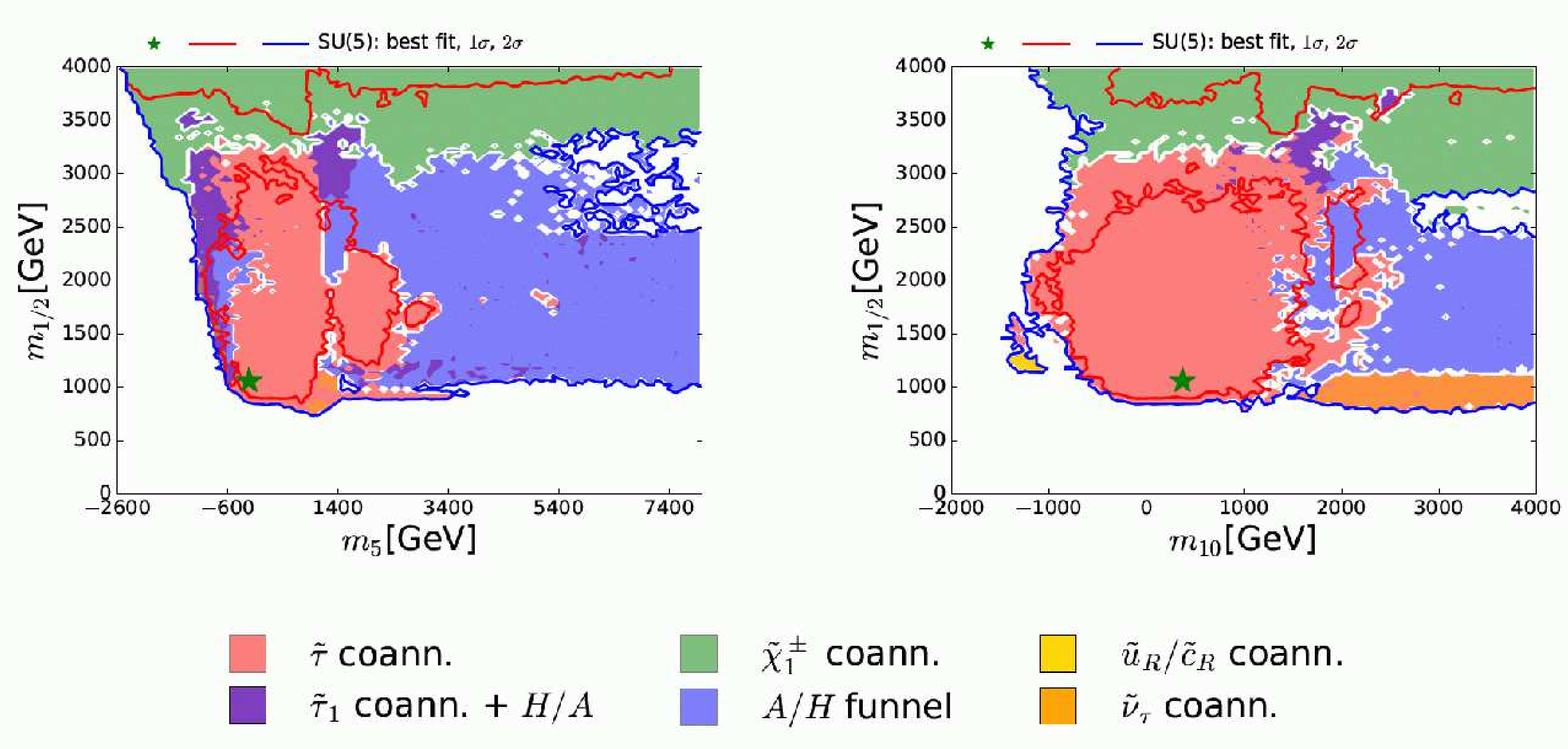
[?2014]


direct detection: NUHM2
NUHM2
preliminary
All these GUT-models are indeed within the red blob. So what about the pMSSM10?
LSP mass [GeV]
arXiv:1310.8327
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
CDMSlite (2013)
SuperCDMS SNOLAB
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
29/09/2014 Kees Jan de Vries; Mastercode; BSM fit workshop
Imperial College London

Results in the SU(5)

Dark Matter annihilation mechanism:

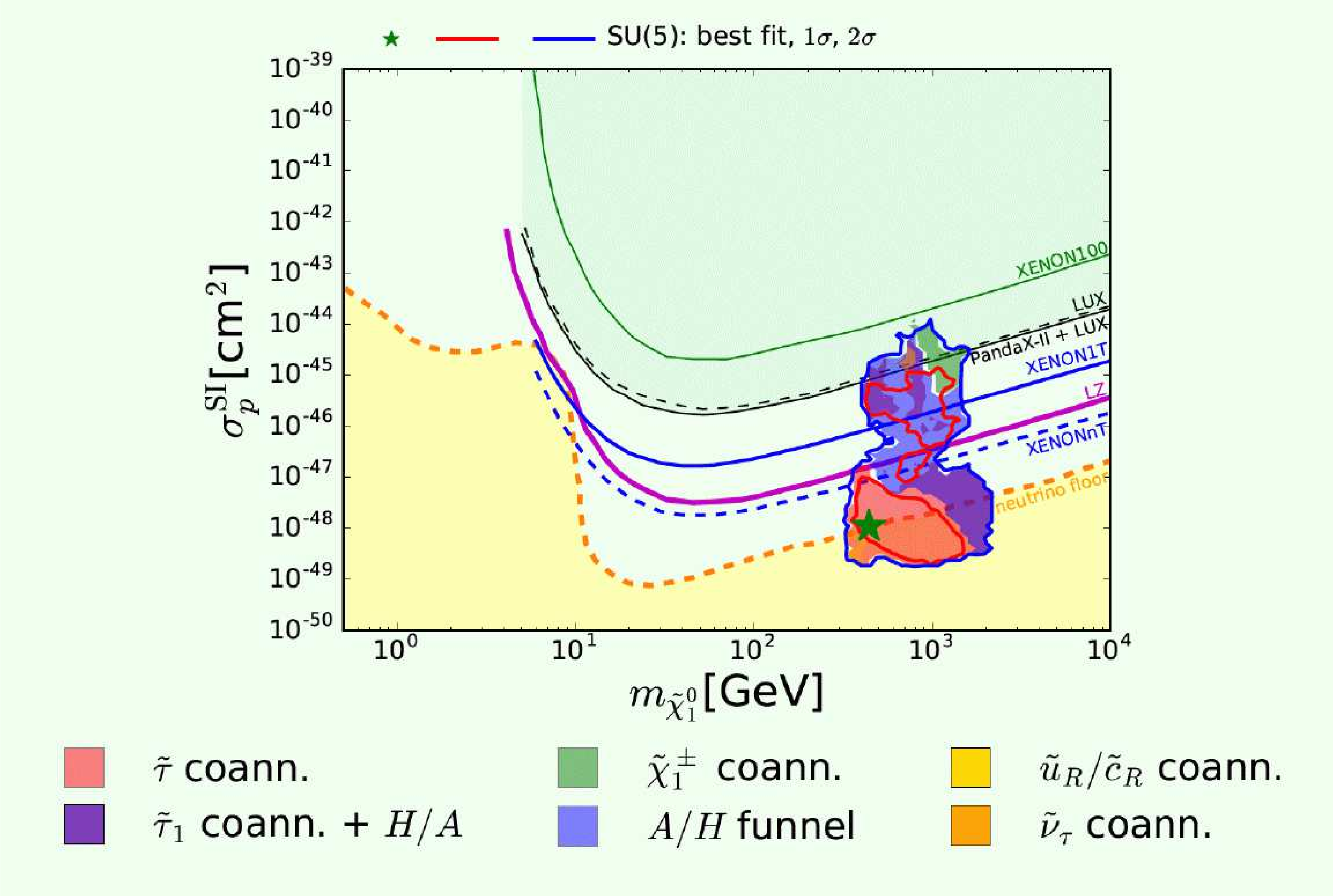
[2016]



$\Rightarrow \tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-annihilation possible

Dark Matter Diret Detection prospects:

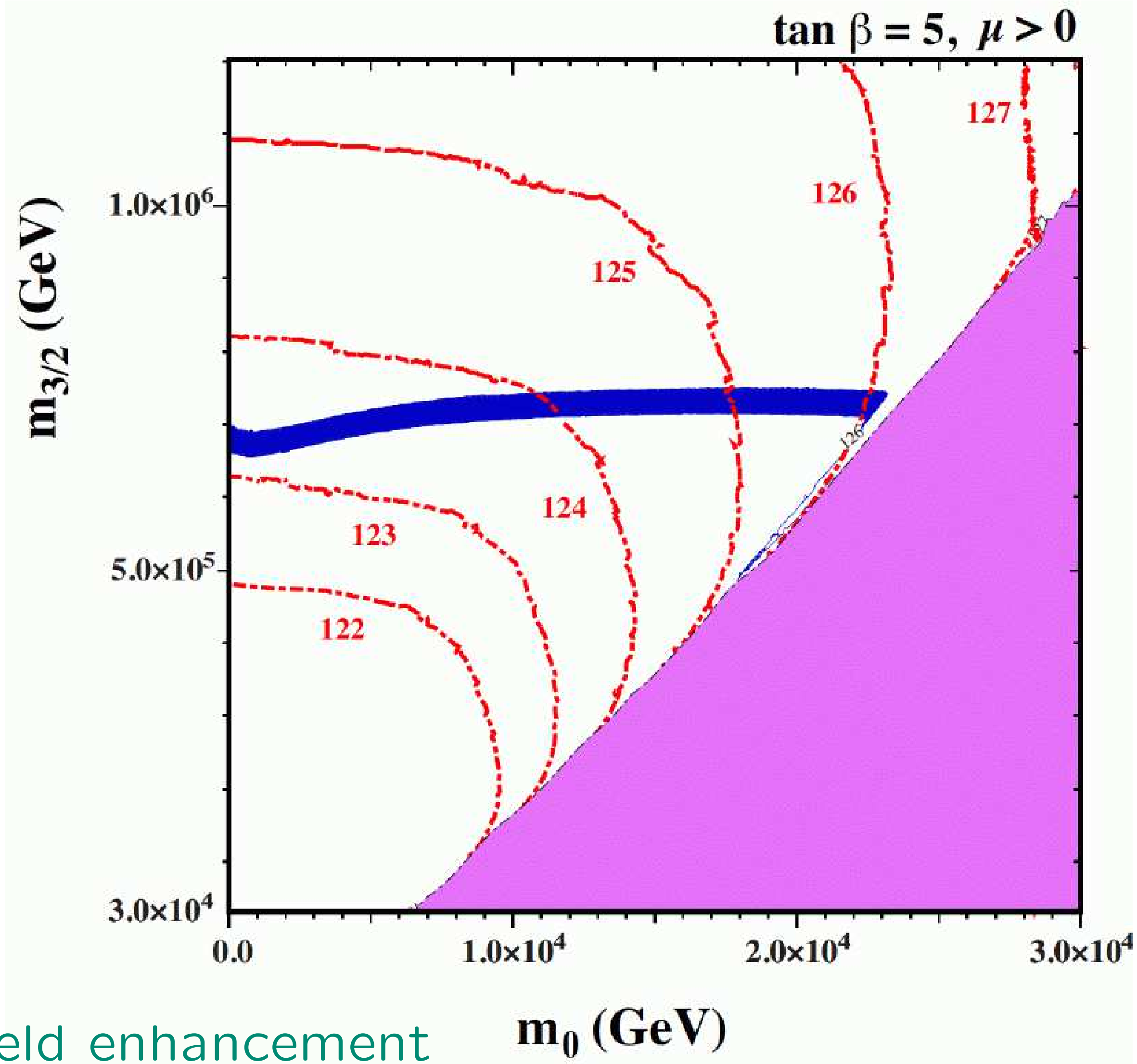
[2016]



Results in the mAMSB

Known fact: Dark Matter requirement restricts $m_{3/2}$:

[2016]



$\Rightarrow$ no Sommerfeld enhancement

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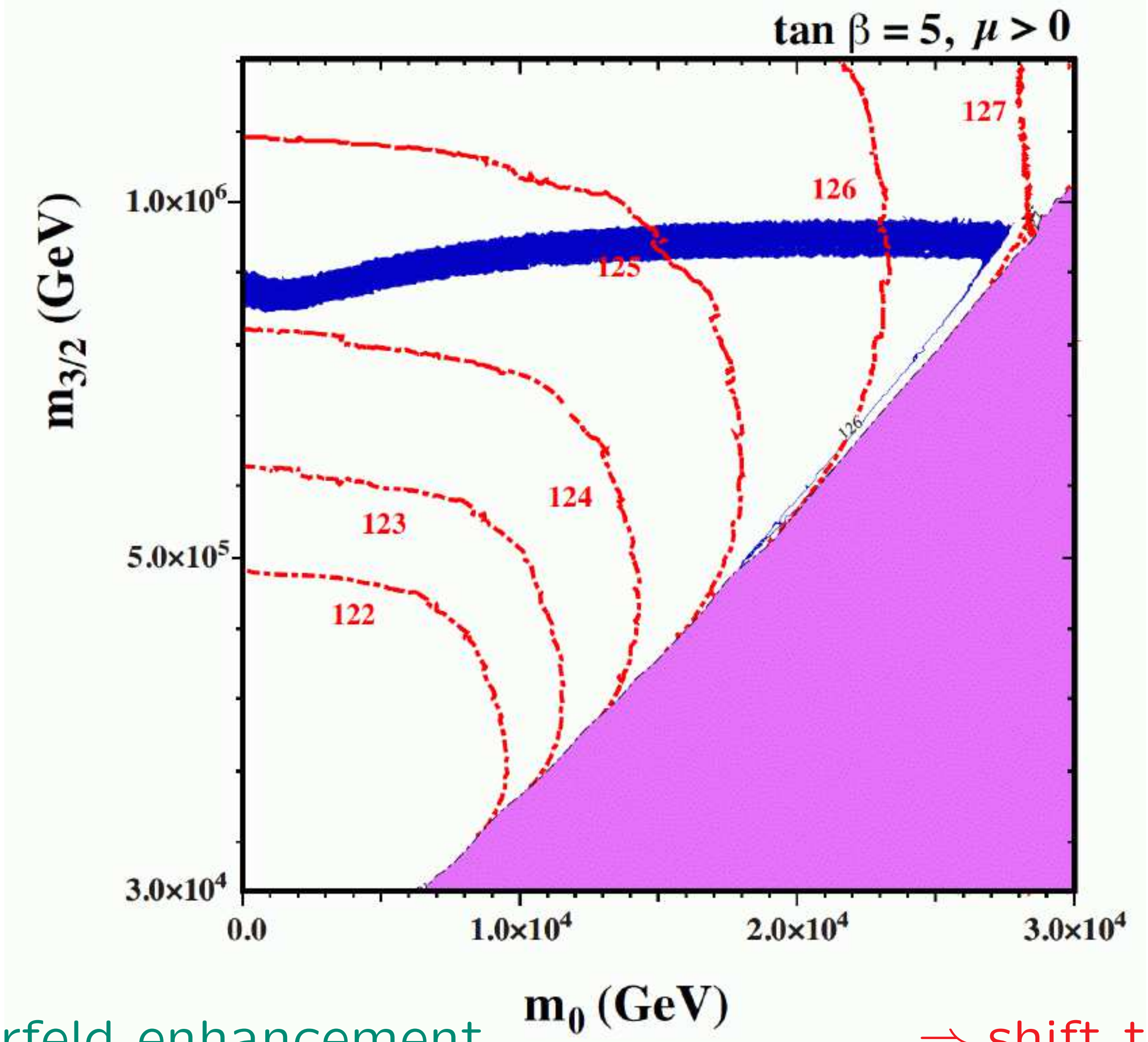
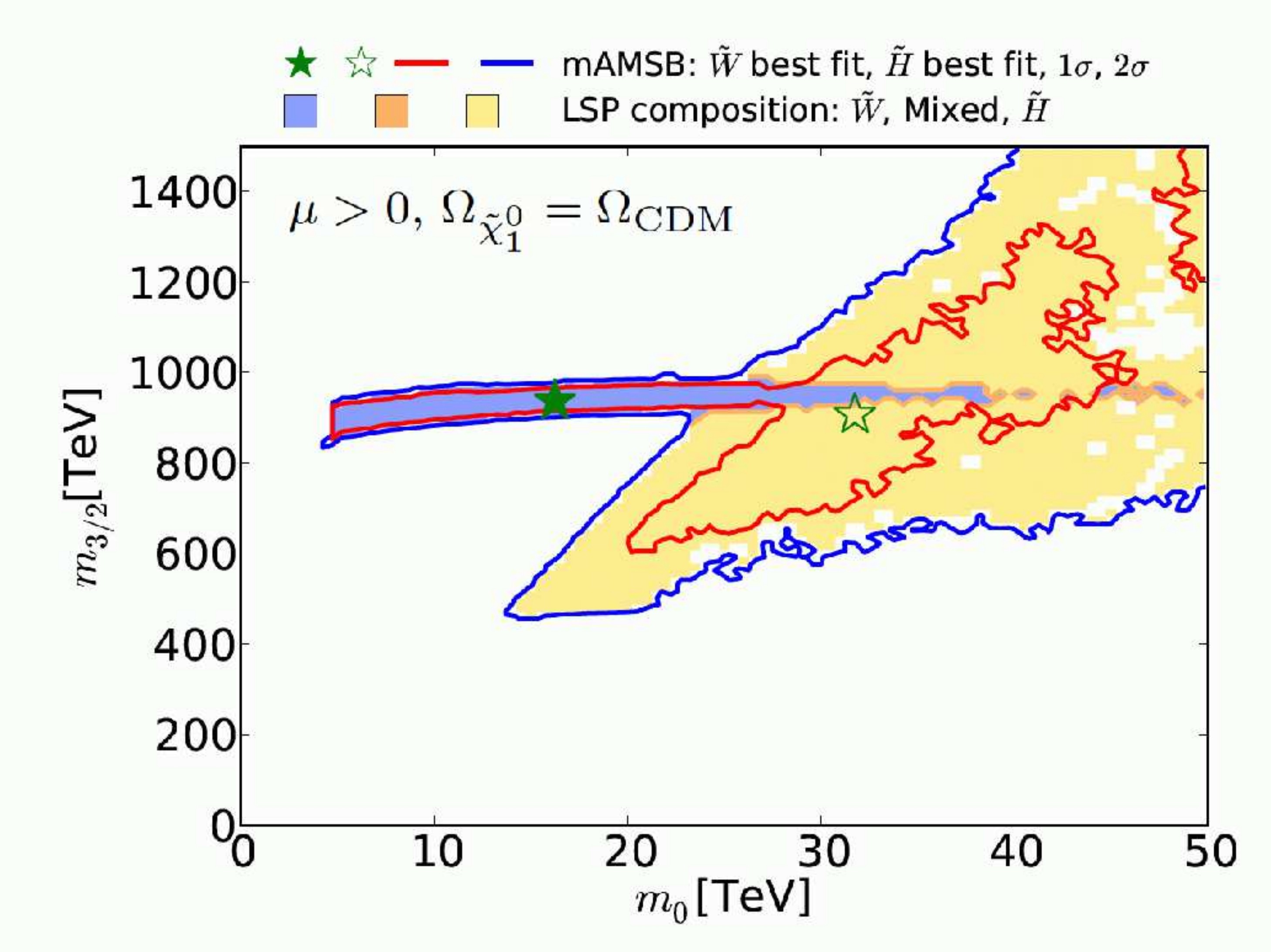


⇒ with Sommerfeld enhancement ⇒ shift to higher $m_{3/2}$

Dark Matter composition:

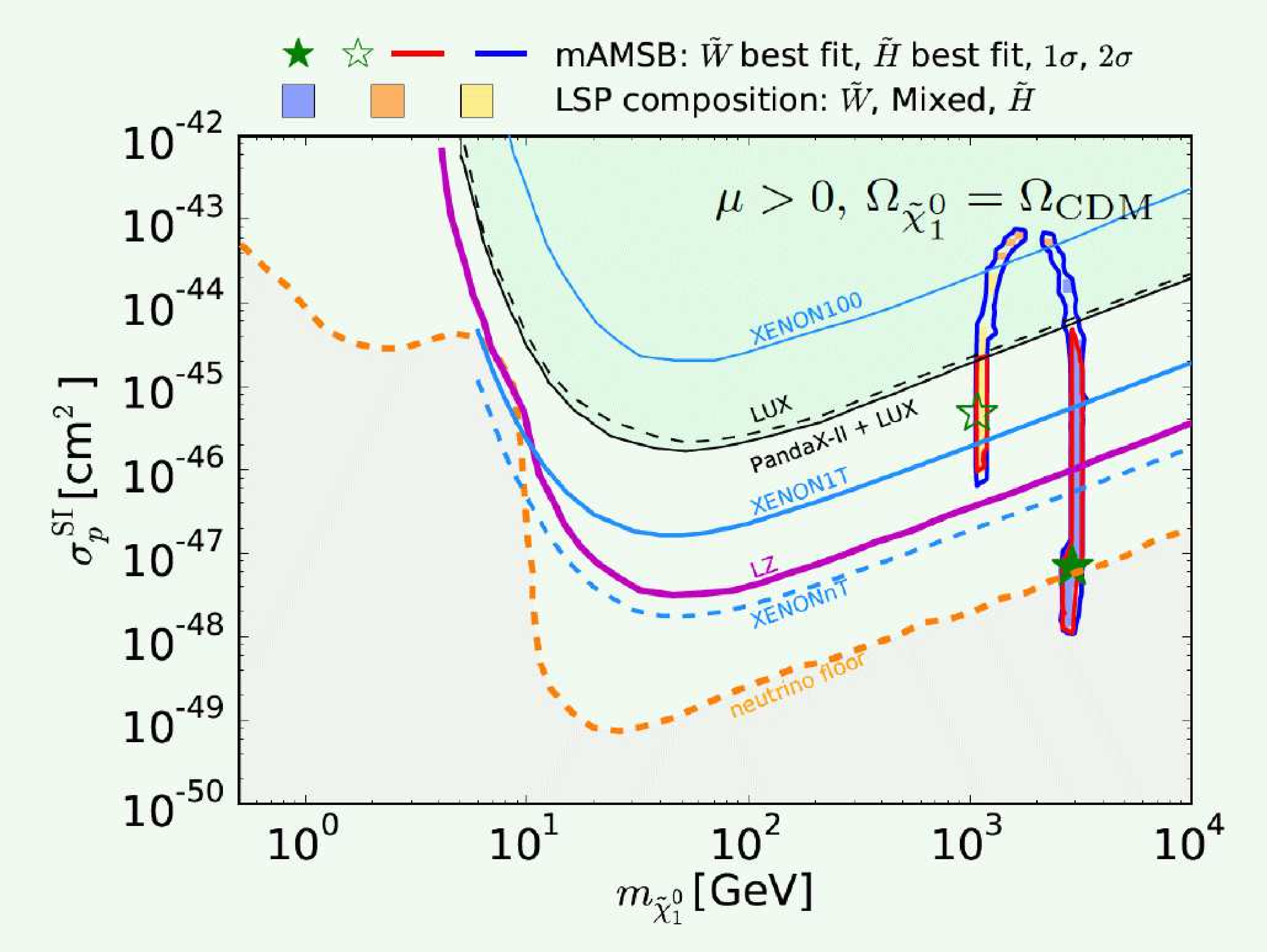
[2016]



$\Rightarrow m_{\tilde{\chi}^0_1} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)

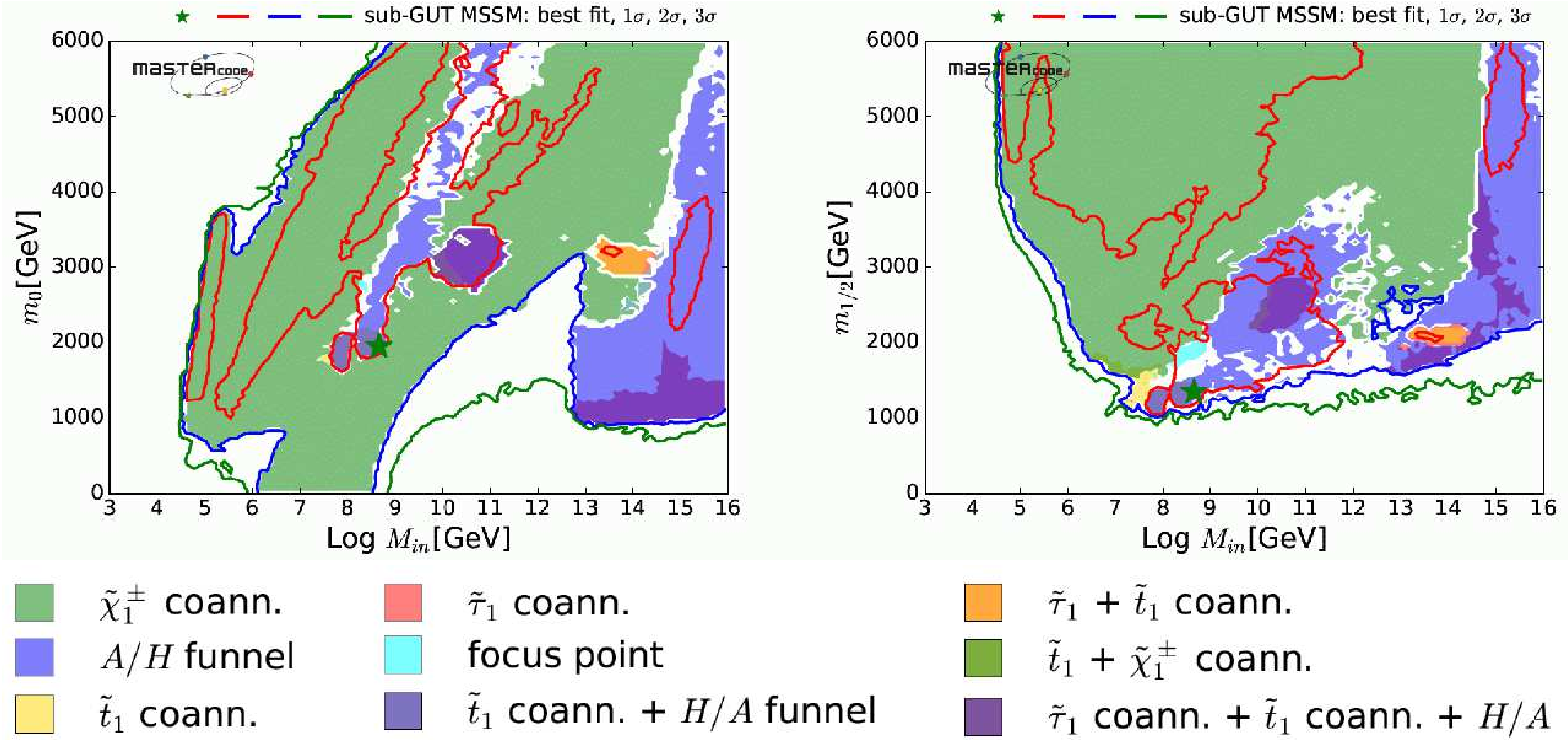
Dark Matter Diret Detection prospects:

[2016]



Results in sub-GUT

[2017]

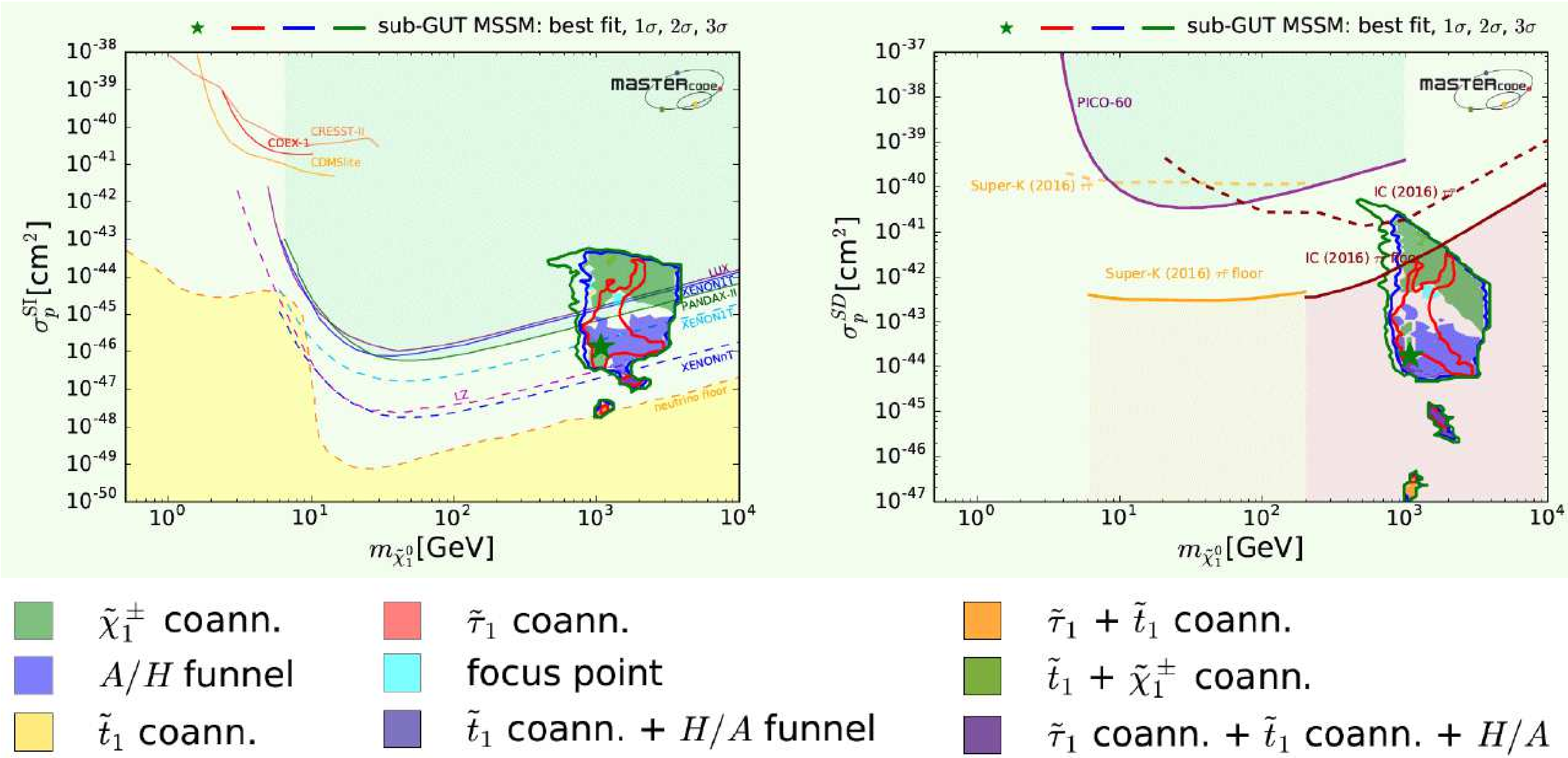


$\Rightarrow$ many DM mechanisms possible

$\Rightarrow$ low $M_{\rm in}$ possible/favored

Dark Matter Diret Detection prospects:

[2017]



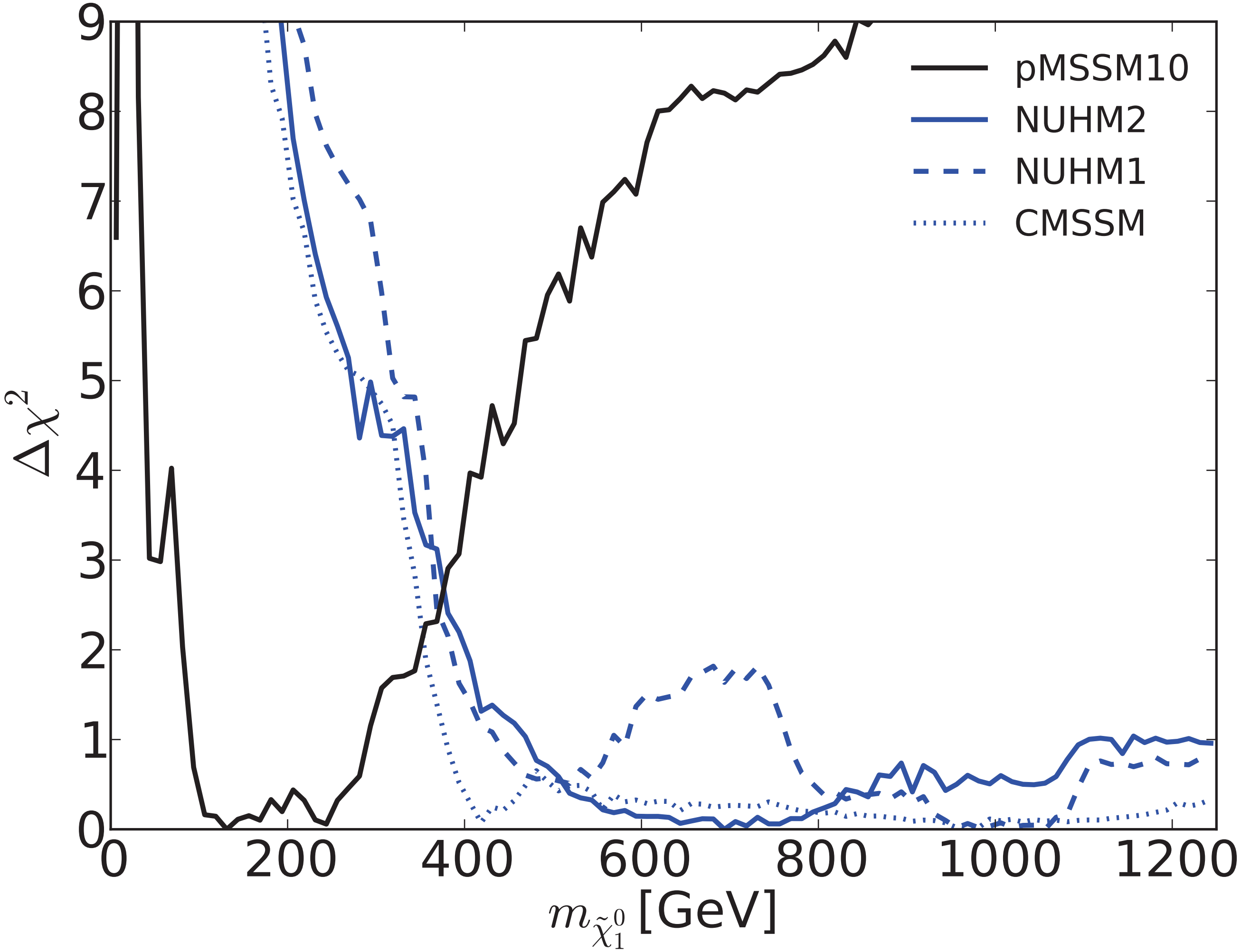
σ_p^{SI} : good prospects, all above the neutrino floor

σ_p^{SD} : unclear prospects, best-fit regions below the neutrino floor

3. Results in the pMSSM11

DM mass: pMSSM10 vs. GUT based models prediction:

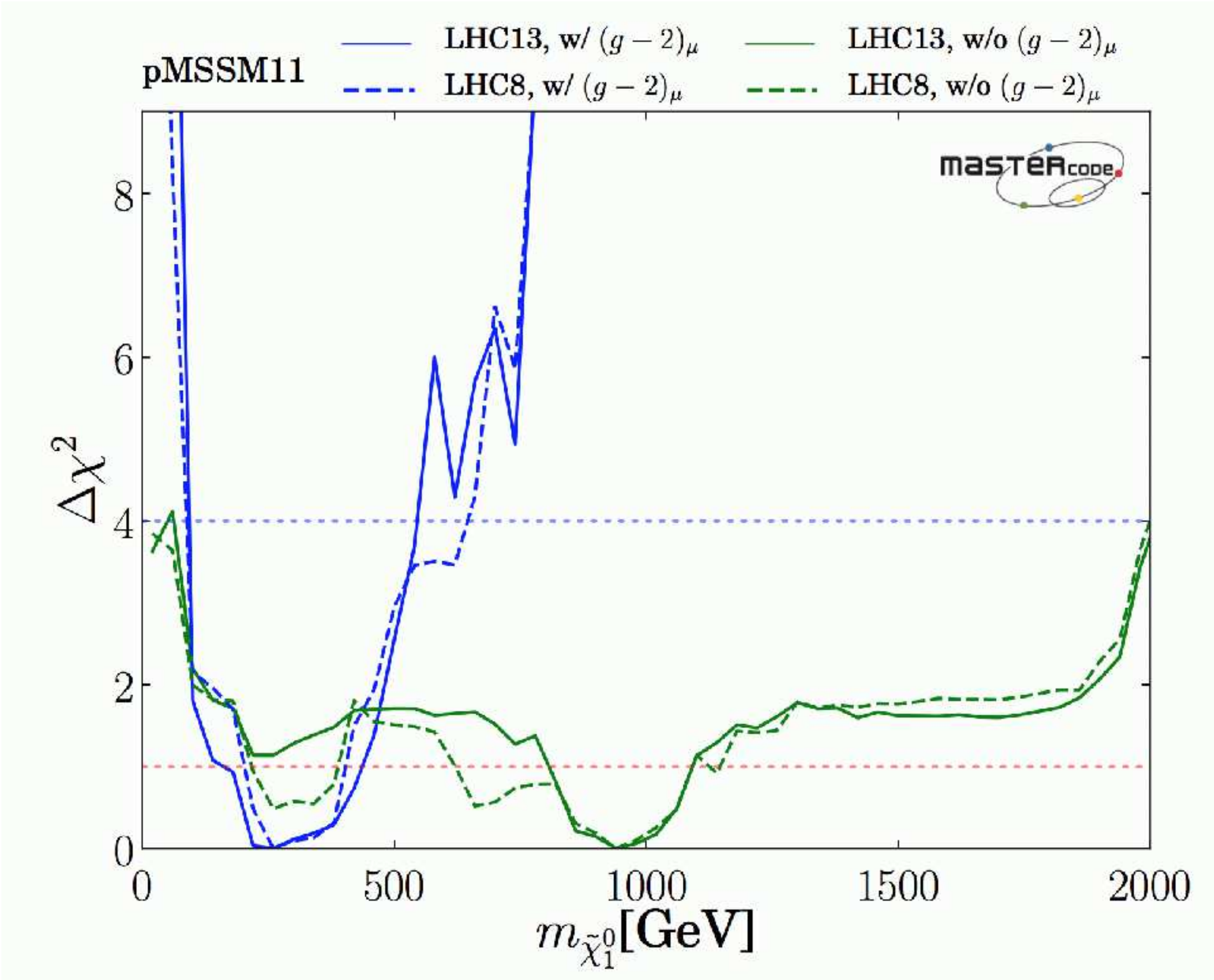
[2015]



⇒ pMSSM10 predicts much lower DM mass than GUT-based models

3. Results in the pMSSM11

DM mass: similar in the pMSSM11:



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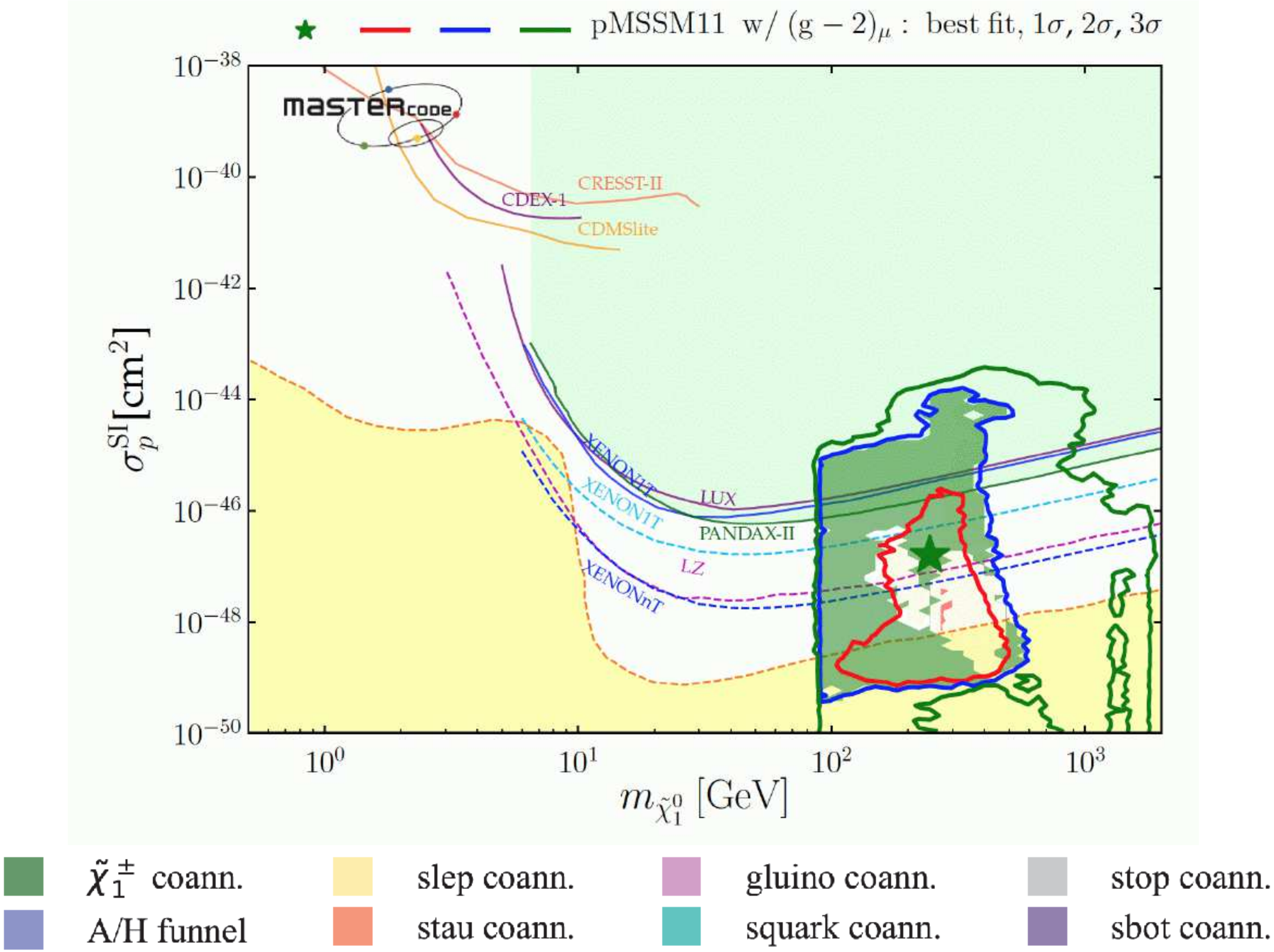
pMSSM prediction: $m_{\tilde{\chi}^0_1}$ vs. $\sigma_p^{\rm SI}$: [2017]

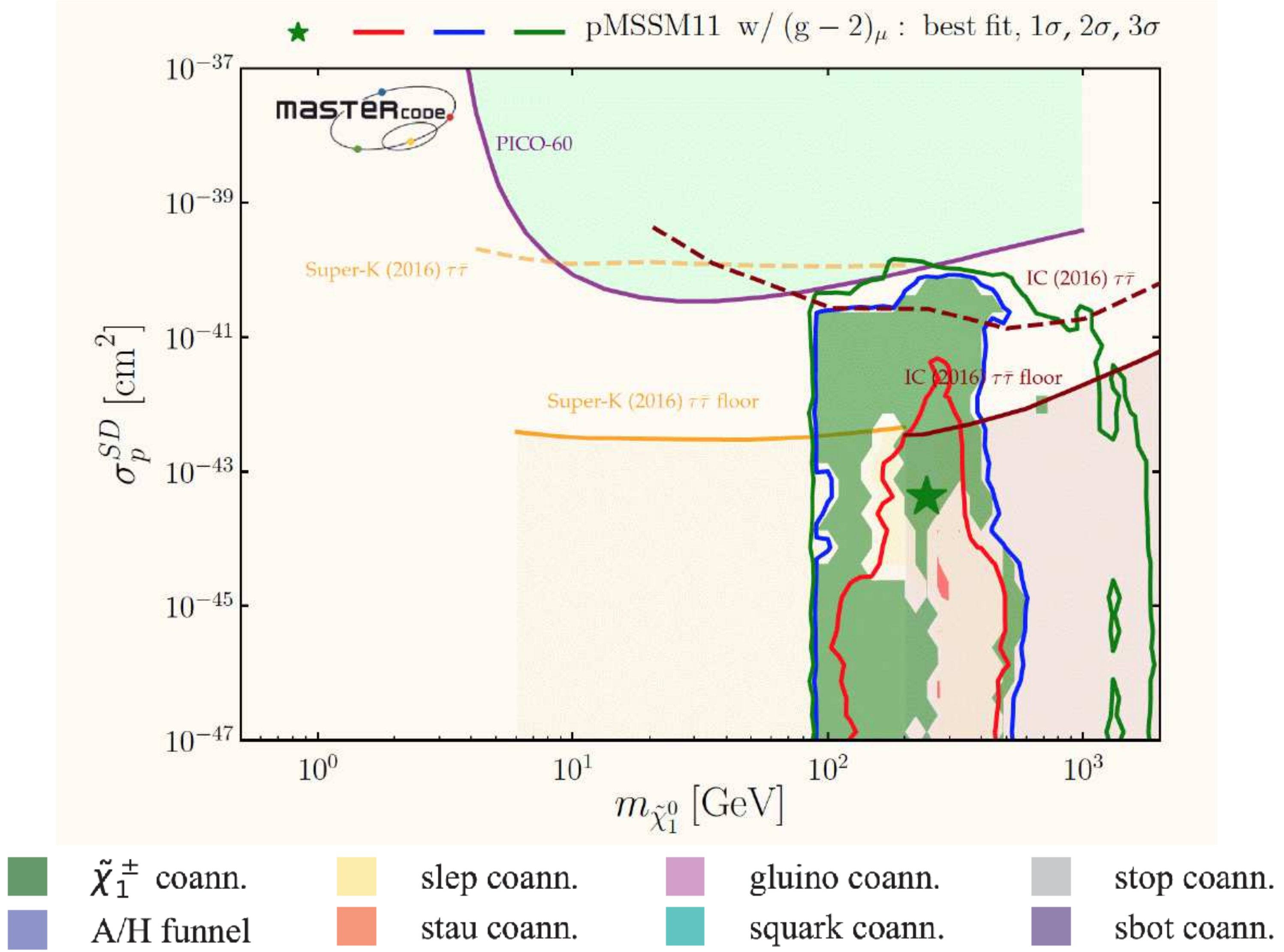


⇒ best-fit point covered by future experiments

⇒ but very low cross sections possible at $1\,\sigma$, below neutrino floor

pMSSM prediction: $m_{\tilde{\chi}^0_1}$ vs. $\sigma_p^{\rm SD}$:

[2017]



⇒ slim prospects for future experiments

⇒ large regions allowed at $1\,\sigma$, below neutrino floor

4. Results in non-SUSY models

⇒ SM + Dirac DM + Leptophobic spin-1 mediator

Lagrangian according to LHC-DM-WG recommendation:

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Scenarios

- Leptophobic, $g^V_{l_{i,j}} = g^A_{l_{i,j}} = 0$ (no constraints from dilepton searches).
- Flavor diagonal, $g^{V/A}_{u/d_{i,j}} = 0$ if $i \neq j$.
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   $g^V_{u/d} \equiv g_{SM}$ $\quad g^A_{u/d} = 0$,
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   pure axial-vector.

[taken from E. Bagnaschi]

MasterCode set-up :

– Frequentist fitting framework written in Python/Cython and C++
– Multinest algorithm is used to sample the parameter space
– udocker used for deployment

Scan ranges:

Parameter	Range	# of Segments
m_Y (mediator)	$(0.1, 5)$ TeV	10
m_χ (DM)	$(0, 2.5)$ TeV	8
g_{SM}	$(10^{-6}, \sqrt{4\pi})$	2
g_{DM}	$(10^{-6}, \sqrt{4\pi})$	2
Total # of segments		320

Constraints:

– DM constraints: relic abundance

$\Rightarrow$ full agreement with ATLAS/CMS results/implementations

– DM constraints: direct detection

$\Rightarrow$ LUX, Xenon1T, PANDAX, PICO60

– Mono-jet contstraints

$\Rightarrow$ `MC5 aMC(N)NLO`, `Fastlim` approach

– di-jet constraints

$\Rightarrow$ `MC5 aMC(N)NLO`, `Fastlim` approach

$\rightarrow$ details in the back-up

General Results

[2019]

- Results for vector mediator model

- Results for axial-vector mediator model $\rightarrow$ back-up

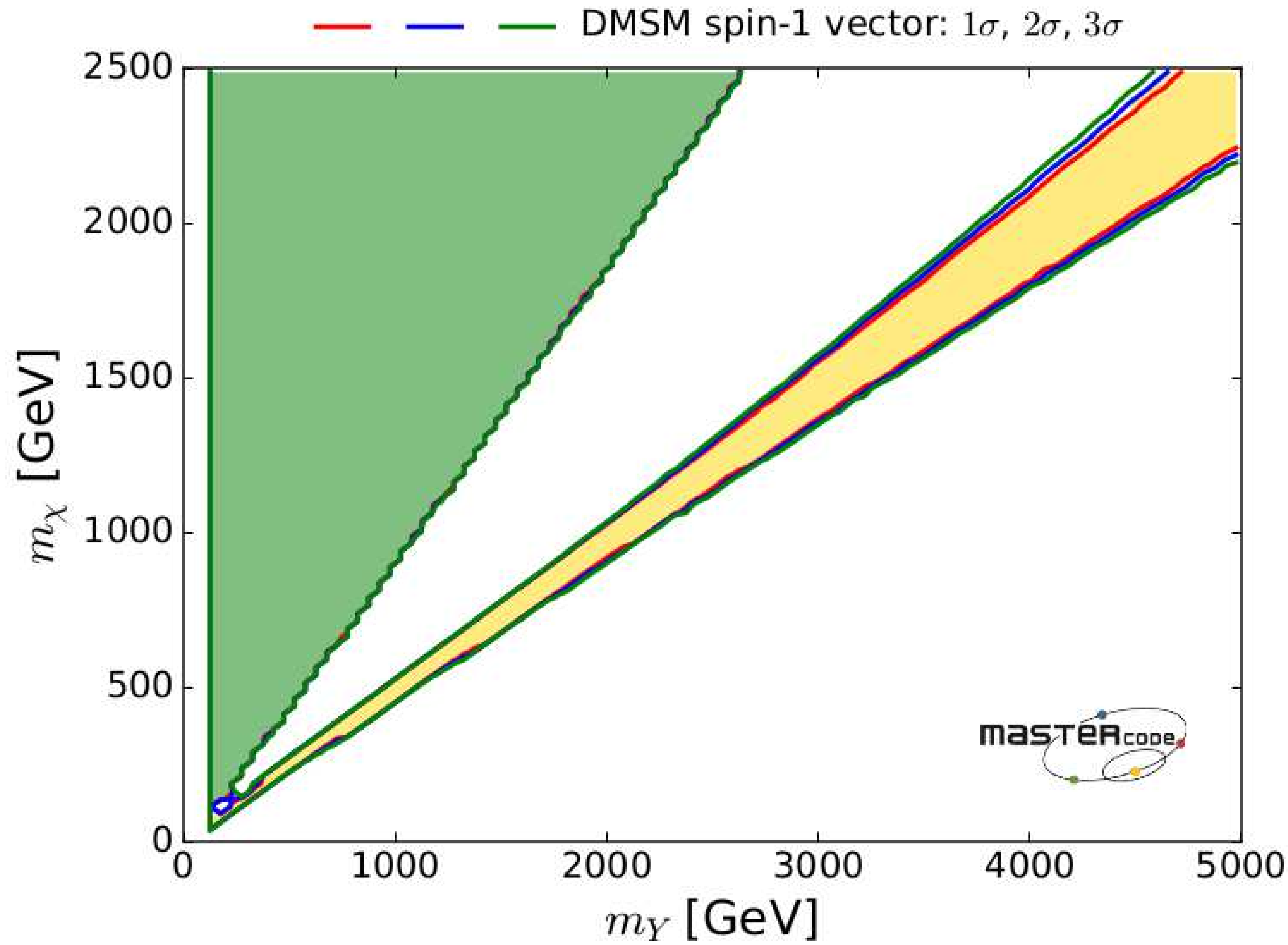
- No restrictions on couplings or masses

- Color coding:

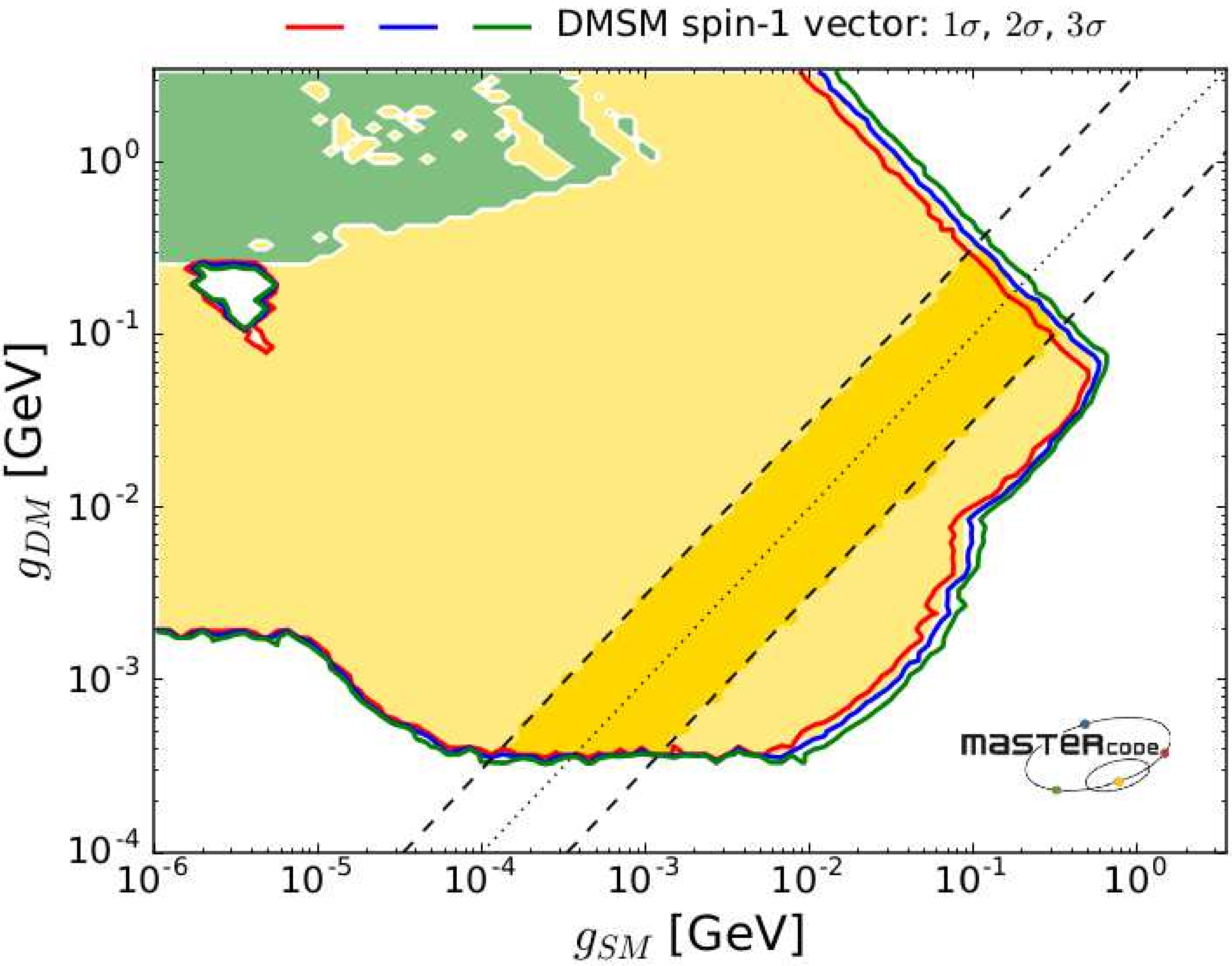
  green: annihilation via t-channel χ exchange
  into pairs of mediator particles Y that subsequently decay
  into SM particles

  yellow: rapid annihilation directly into SM particles
  via the s-channel Y resonance

Vector mediator (I): [2019]

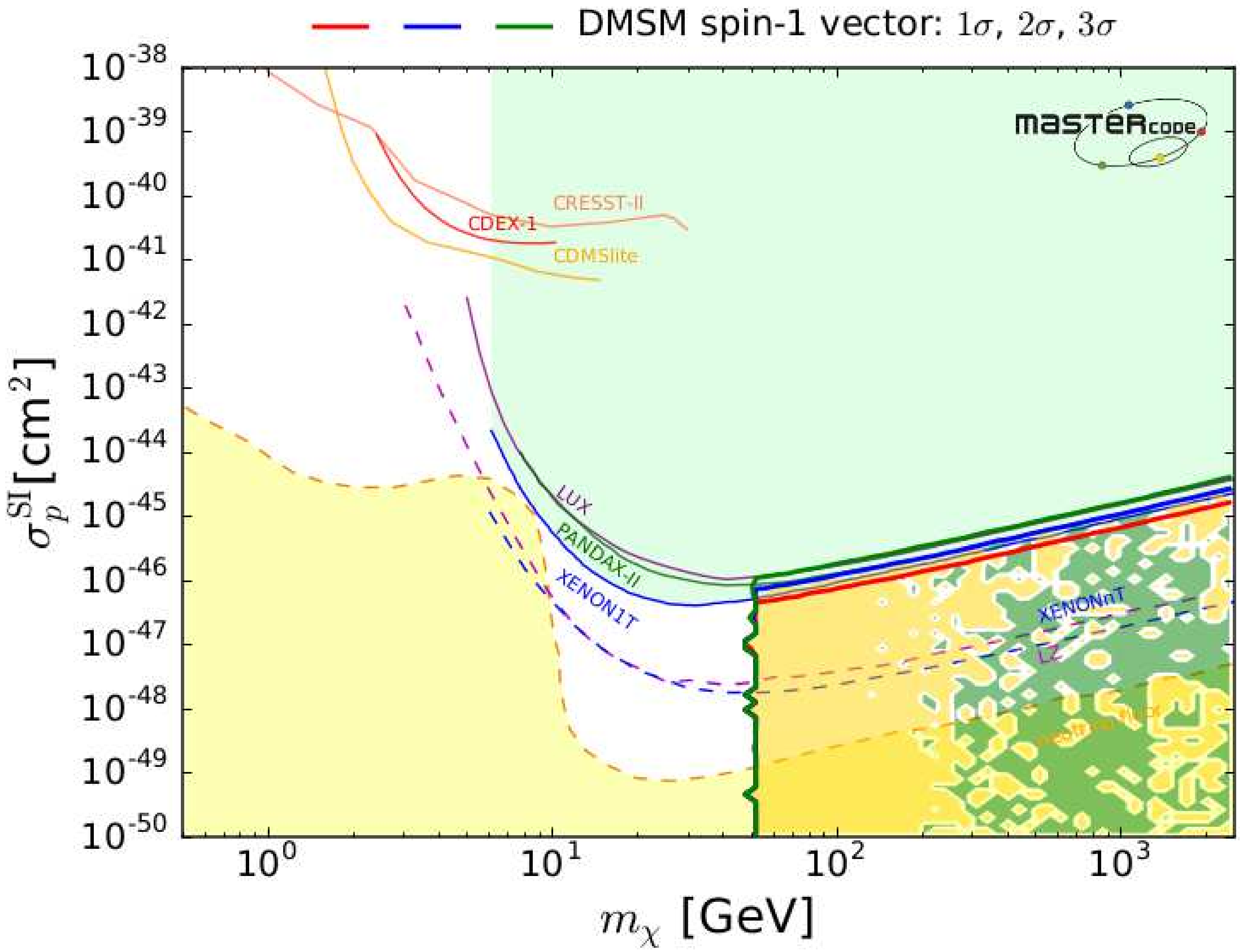


$\Rightarrow$ clear separation between s- and t-channel



$\Rightarrow$ large ranges allowed, t-channel only for $g_{\rm DM} \gg g_{\rm SM}$

Vector mediator (III): [2019]



$\Rightarrow$ mixed prospects, both for s- and t-channel case

Towards UV completions

So far no UV completion considered!

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In any UV completion the spin-one boson could be expected to have comparable couplings to SM and DM particles, modulo possible group-theoretical factors and mixing angles!

$$\boxed{g_{\mathsf{DM}}/g_{\mathsf{SM}} = \mathcal{O}\,(1)}$$

Towards UV completions

So far no UV completion considered!

In any UV completion the spin-one boson could be expected to have comparable couplings to SM and DM particles, modulo possible group-theoretical factors and mixing angles!

$$\boxed{g_{\text{DM}}/g_{\text{SM}} = \mathcal{O}\,(1)}$$

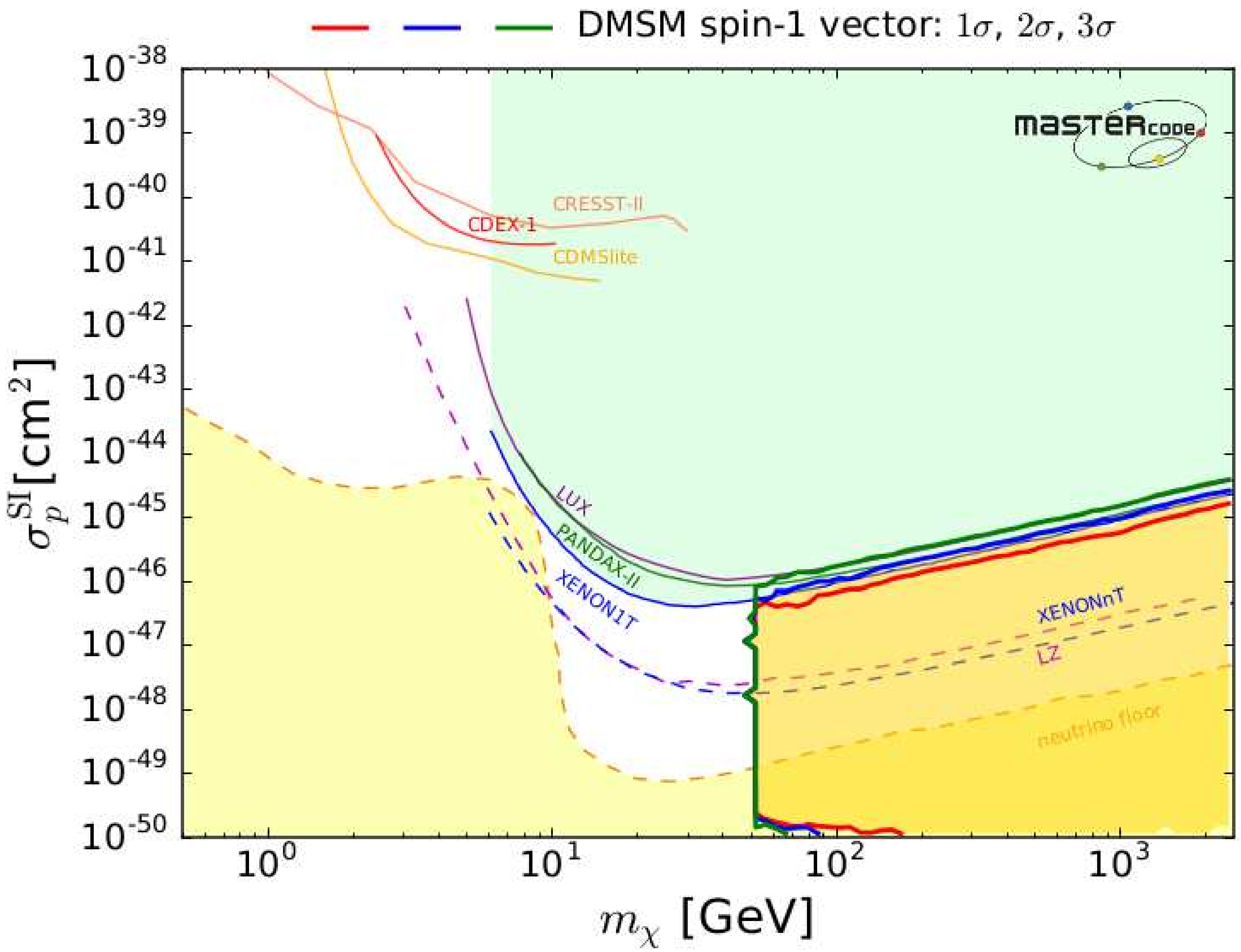
$$\boxed{1/3 < g_{\text{DM}}/g_{\text{SM}} < 3}$$

$\Rightarrow$ dark yellow regions

$\Rightarrow$ s-channel favored!

Vector mediator: towards UV completions

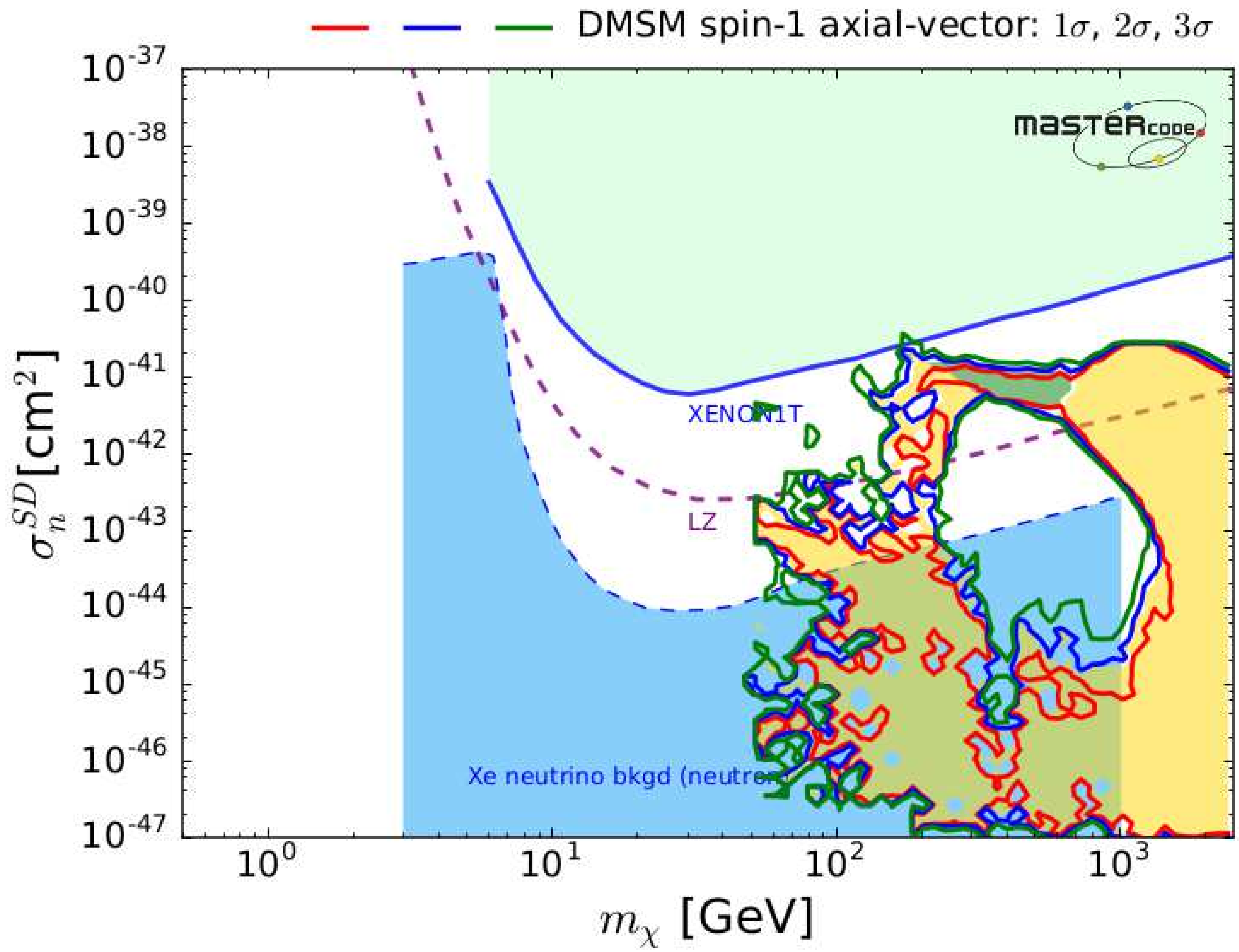
[2019]



⇒ mixed prospects for discovery

Axial-vector mediator: towards UV completions

[2019]



$\Rightarrow$ t-channel can fully be probed, s-channel only partially

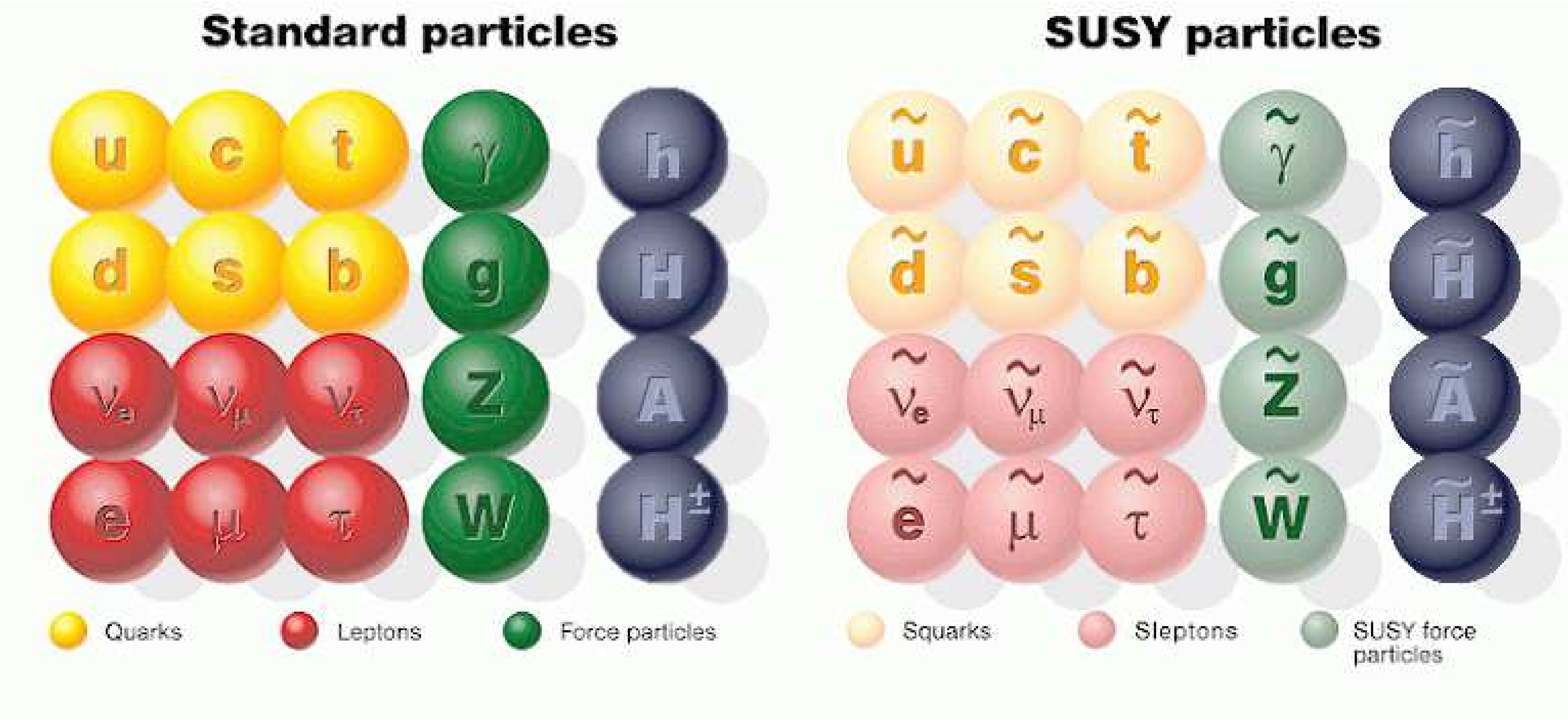
5. Conclusinos

- SUSY constrained: CMSSM, NUHM, SU(5), mAMSB, sub-GUT
  SUSY general: pMSSM11, . . .
- Our tool: MasterCode: combination of all relevant data!
- CMSSM, NUHM1, NUHM2: – $m_{\tilde{\chi}_1^0} \gtrsim 400$ GeV neutrino floor
  – best-fit regions (mostly) above/at/below
- SU(5): – stau co-ann., but also $\tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-ann. possible
  – $m_{\tilde{\chi}_1^0}$ as in CMSSM, NUHM1, NUHM2
- mAMSB: – $m_{\tilde{\chi}_1^0} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)
  – DD: wino at neutrino floor, higgsino tested by next round
- pMSSM11: – $m_{\tilde{\chi}_1^0} \lesssim 500$ GeV; important: chargino co-annihilation
  – σ_p^{SI} partially cov. at future exp., σ_p^{SD} below neutrino floor
- SM + Dirac DM + Leptophobic spin-1 mediator
  $\Rightarrow$ MasterCode approach: full fit of the model (no simplifying ass.)
  Vector mediator: s- and t-channel separated, mixed prospects for DD
  Axialvector: s- and t-channel continous, mixed prospects for DD
  UV-completions: $1/3 < g_{\mathrm{SM}}/g_{\mathrm{DM}} < 3 \Rightarrow s$-channel preferred
  $\Rightarrow$ prospects for DD not improved


Further Questions?

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

most general case:

$\Rightarrow$ 105 new parameters: masses, mixing angles, phases

$\Rightarrow$ no model missed (within the MSSM)

$\Rightarrow$ $\mathcal{O}(100)$ parameters difficult to handle

B. Constrained models:

CMSSM, NUHM1, NUHM2, SU(5), mAMSB, sub-GUT, . . . :

assumption on the scenario that achieves spontaneous SUSY breaking

$\Rightarrow$ prediction for soft SUSY-breaking terms
in terms of small set of parameters

$\Rightarrow$ easy to handle

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

$$\left.\begin{array}{l} m_0 : \text{universal scalar mass parameter} \\ m_{1/2} : \text{universal gaugino mass parameter} \\ A_0 : \text{universal trilinear coupling} \end{array}\right\} \text{at the GUT scale}$$

$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

$\Rightarrow$ particle spectra from renormalization group running to weak scale

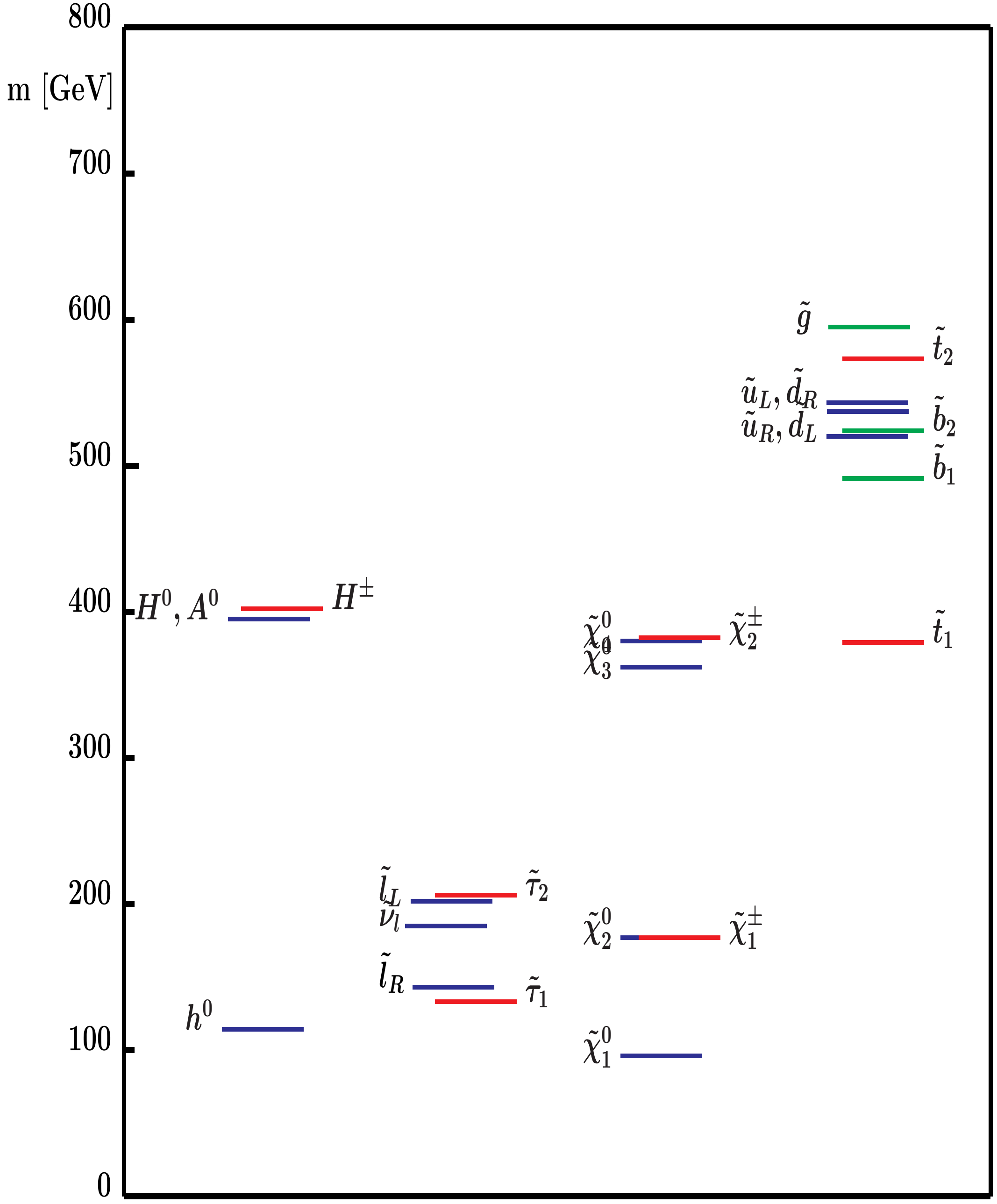
$\Rightarrow$ Lightest SUSY particle (LSP) is the lightest neutralino $\Rightarrow$ DM!

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A as free parameters at the EW scale

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu \text{ and } M_A$$

GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A and μ as free parameters at the EW scale

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \text{ and } M_A$$

GUT based models: 4.) SU(5) GUT:

Assumption I:

no unification of scalar Higgs parameter at the GUT scale

($\Rightarrow$ effectively M_A and μ as free parameters at the EW scale)

Assumption II:

$$(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i, \;\; (\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$$

$\Rightarrow$ Scenario characterized by

$$m_5,\ m_{10},\ m_{1/2},\ A_0,\ \tan\beta,\ m_{H_u},\ m_{H_d}$$

GUT based models: 5.) mAMSB:

mAMSB scenario characterized by

$$m_{3/2}, m_0, \tan\beta, \mathrm{sign}(\mu)$$

$m_{3/2} = \langle F \rangle / M_{\mathrm{Planck}}$: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term
introduced in order to keep squares of slepton masses positive

typical feature: very small neutralino–chargino mass difference
$\Rightarrow \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 + \pi^{\pm}$ with very soft pions

GUt based models: 6.) sub-GUT:

Based on CMSSM with unification at $M_{\text{GUT}} \sim 2 \cdot 10^{16}$ GeV:

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

Unification is assumed at $M_{\text{in}} \leq M_{\text{GUT}}$:

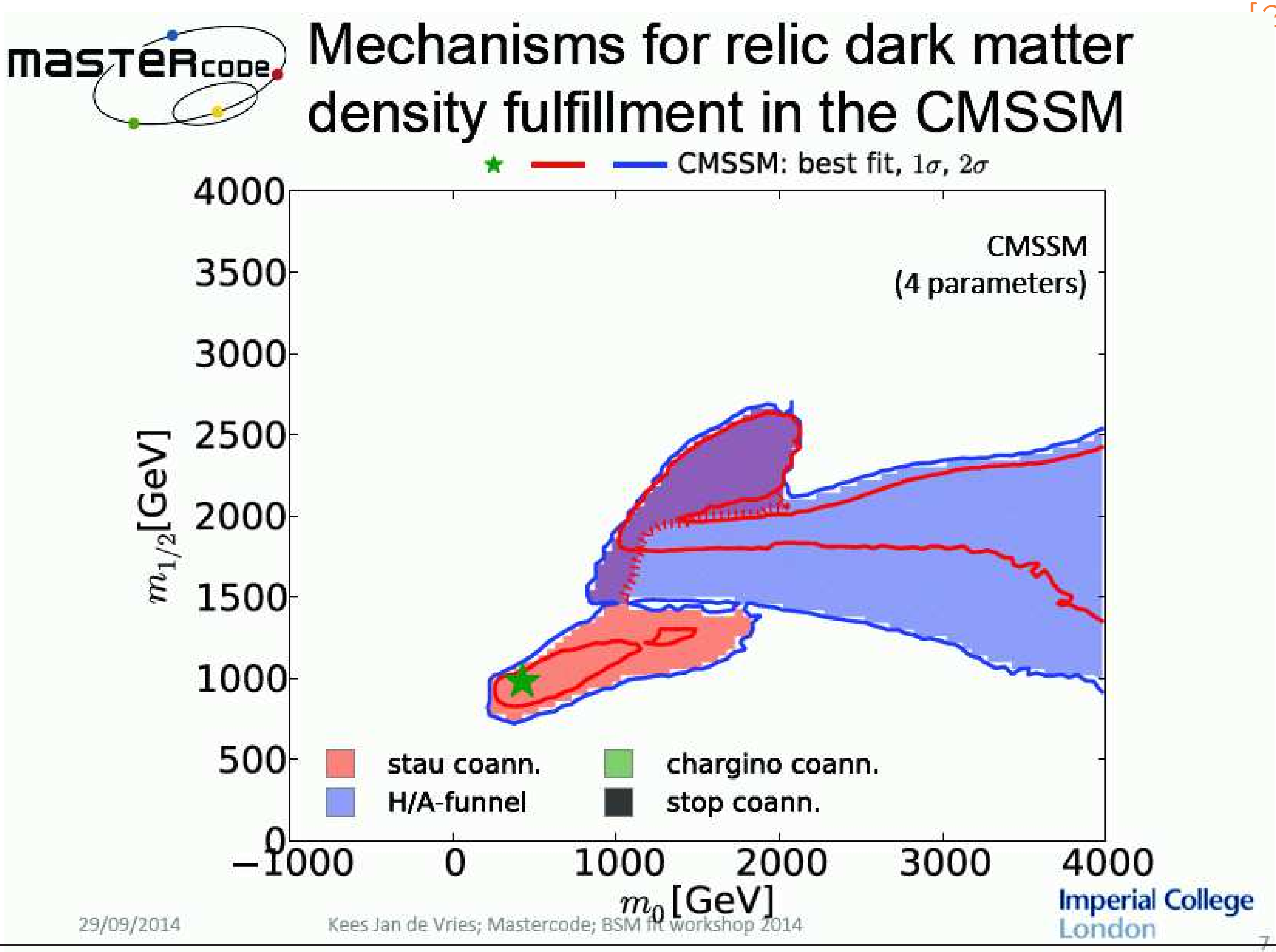
$\Rightarrow$ Scenario characterized by

$$M_{\text{in}},\ m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

Possible realization in "mirage unification"
warped extra dimensions
...

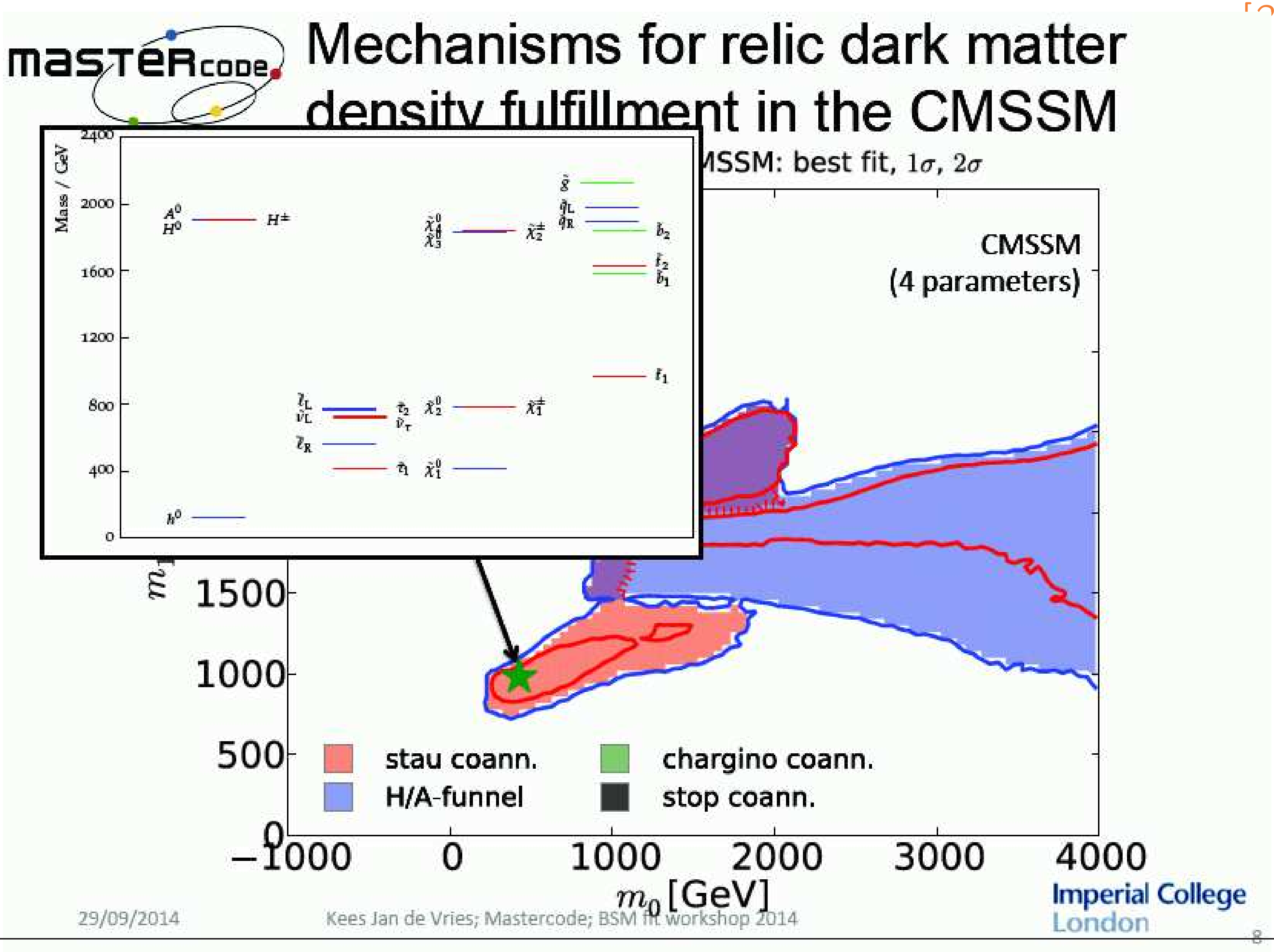
CMSSM DM prediction

[2014]



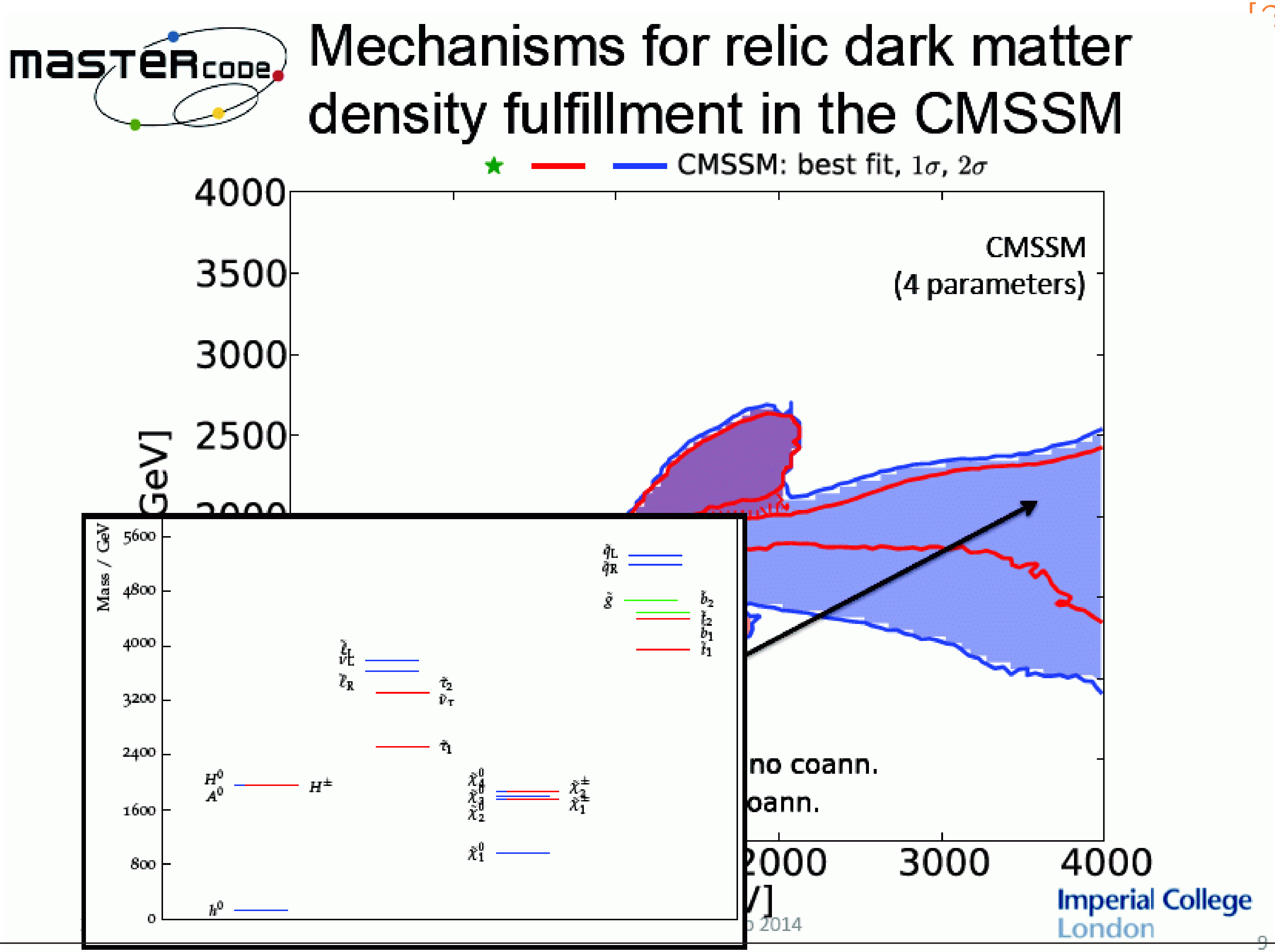
CMSSM DM prediction

[2014]



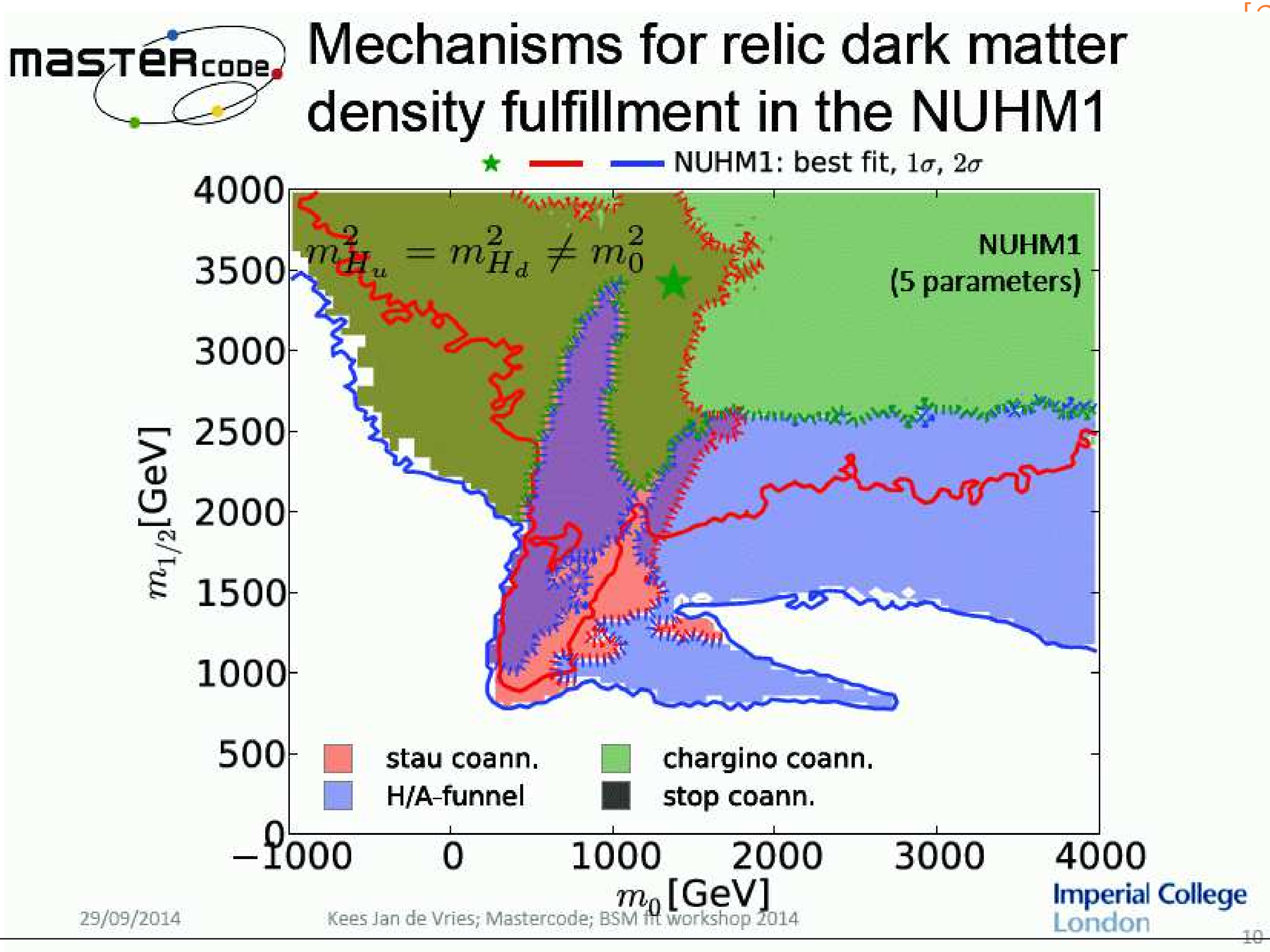
CMSSM DM prediction

[2014]



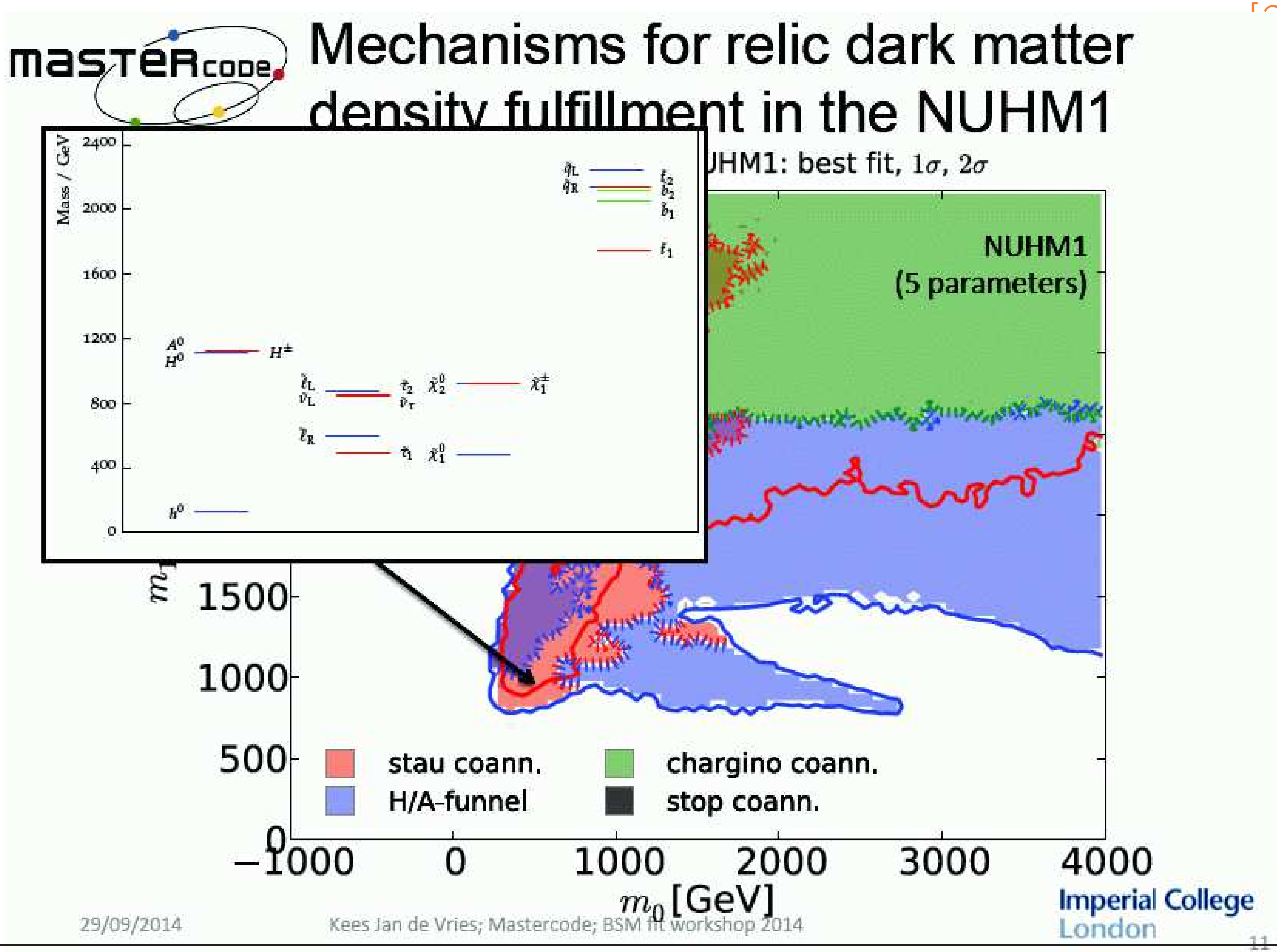
NUHM1 DM prediction

[2014]



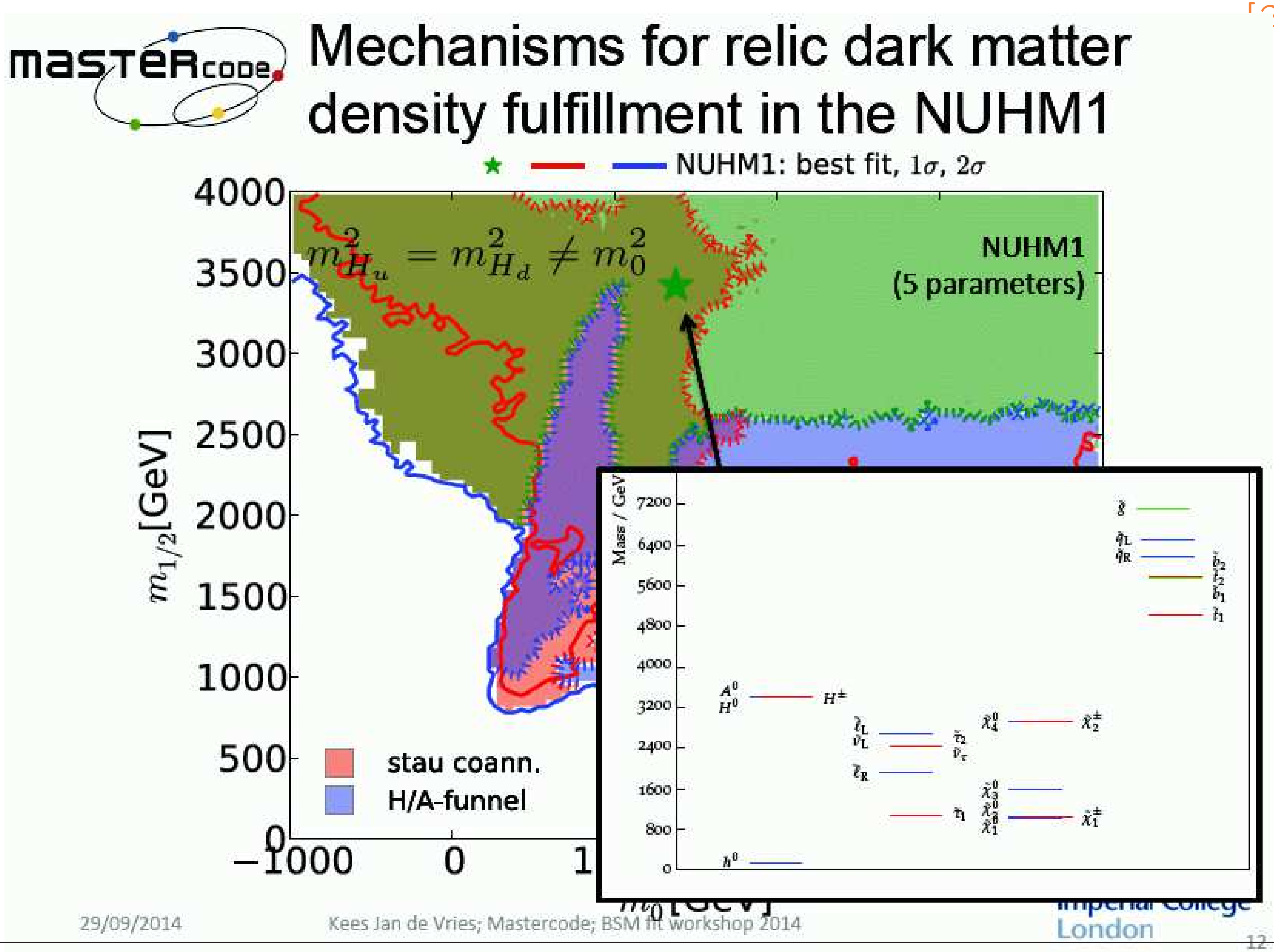
NUHM1 DM prediction

[2014]



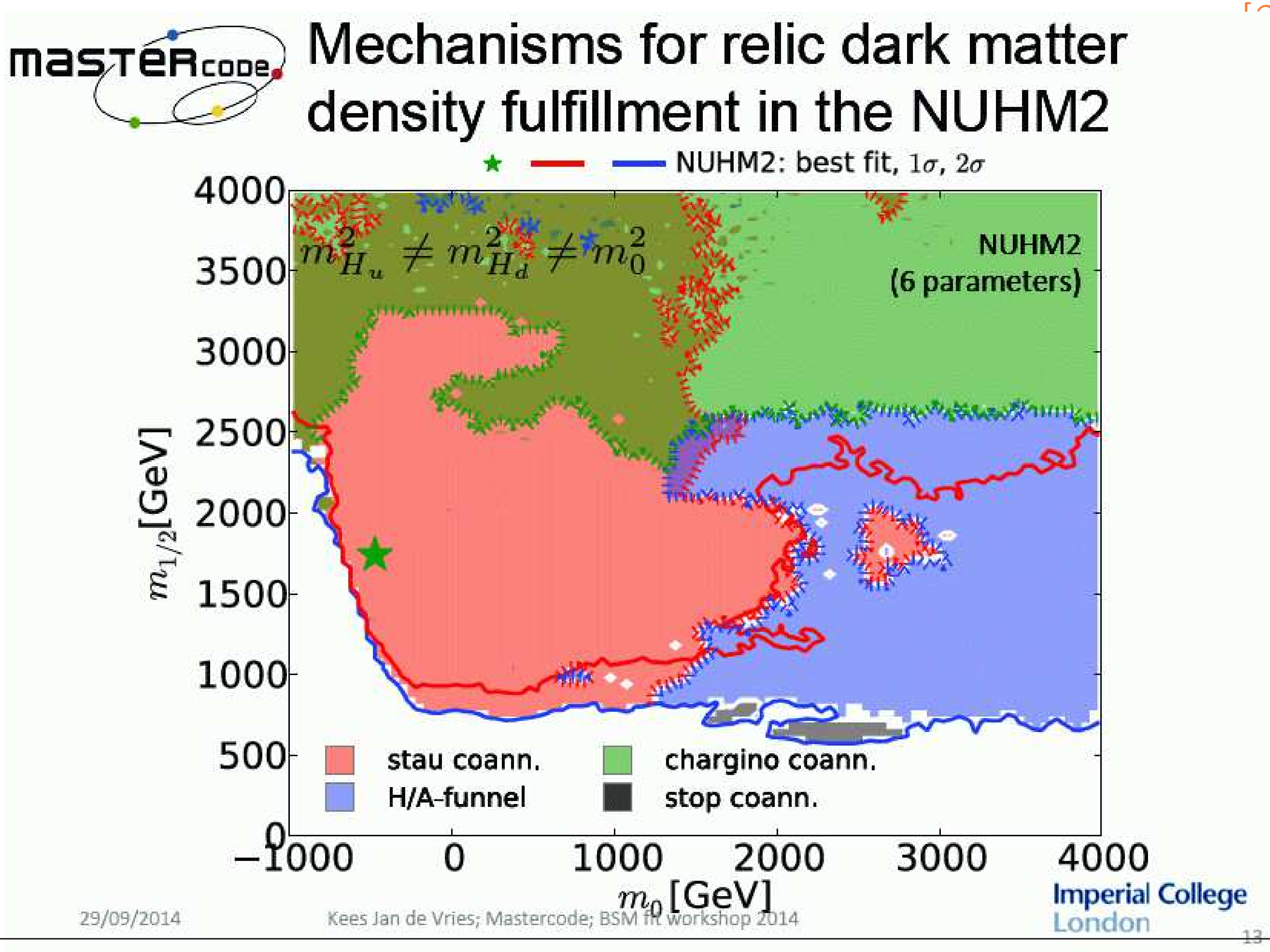
NUHM1 DM prediction

[2014]



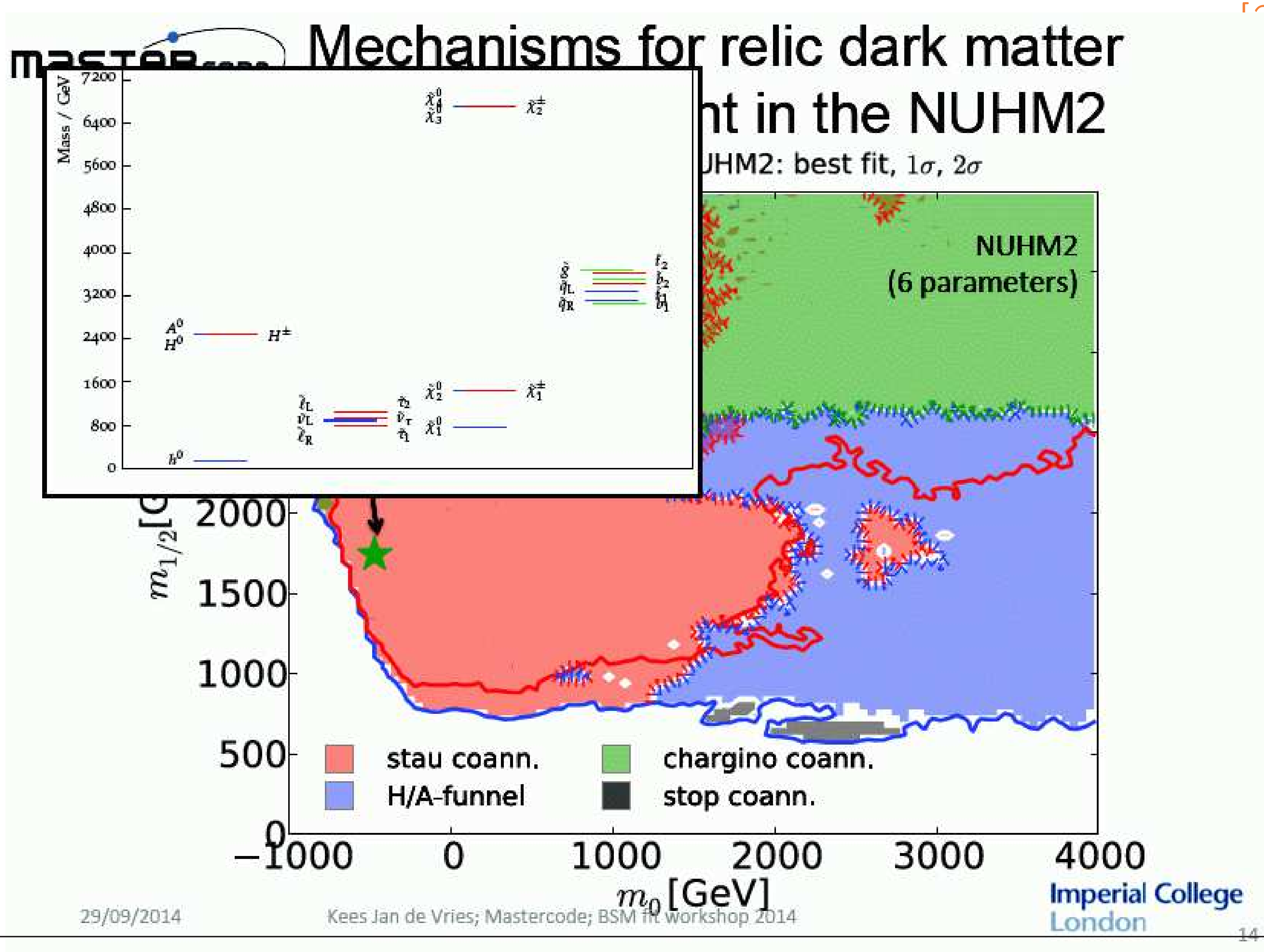
NUHM2 DM prediction

[2014]



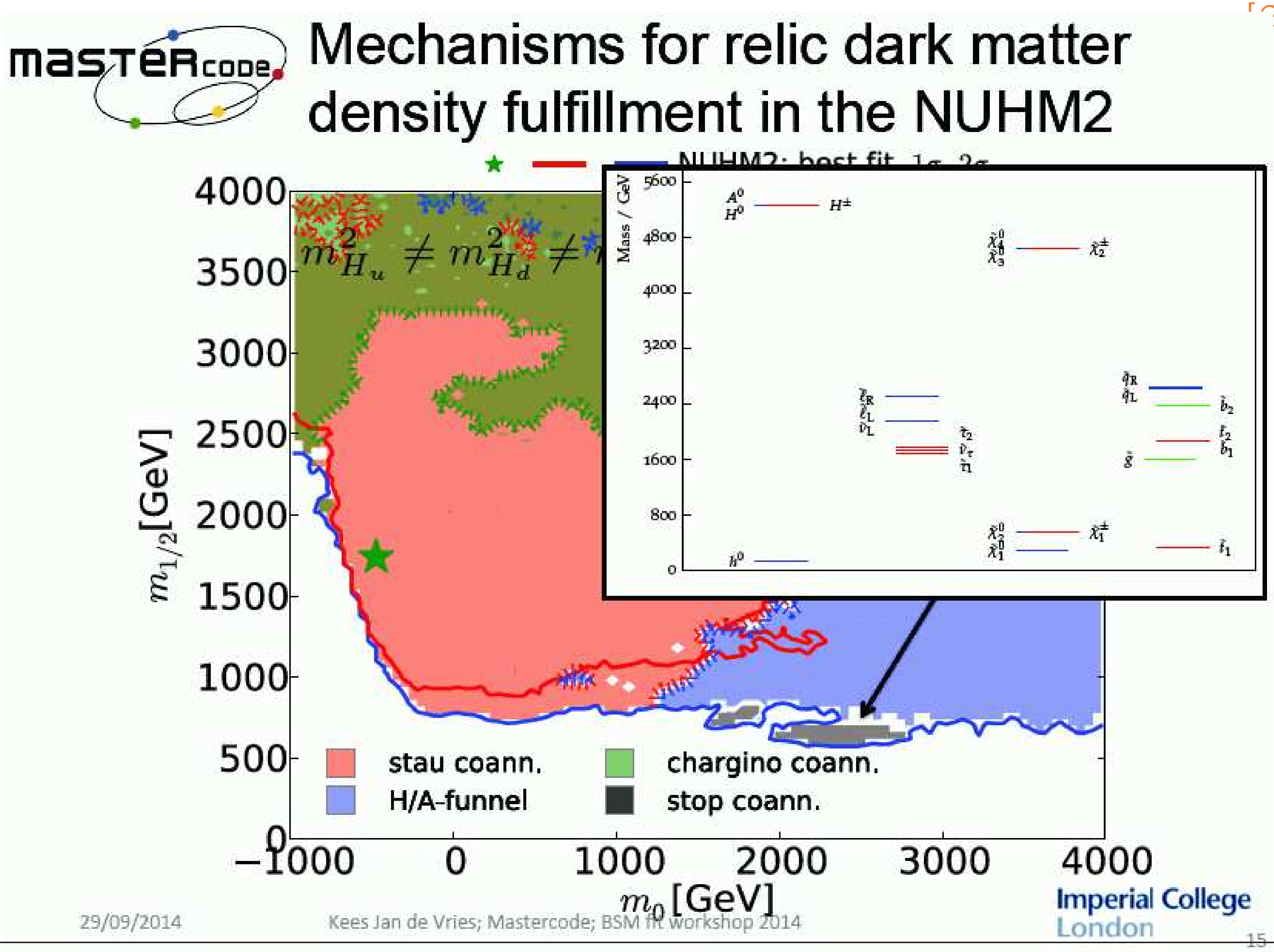
NUHM2 DM prediction

[?2014]



NUHM2 DM prediction

[2014]



5. Conclusinos

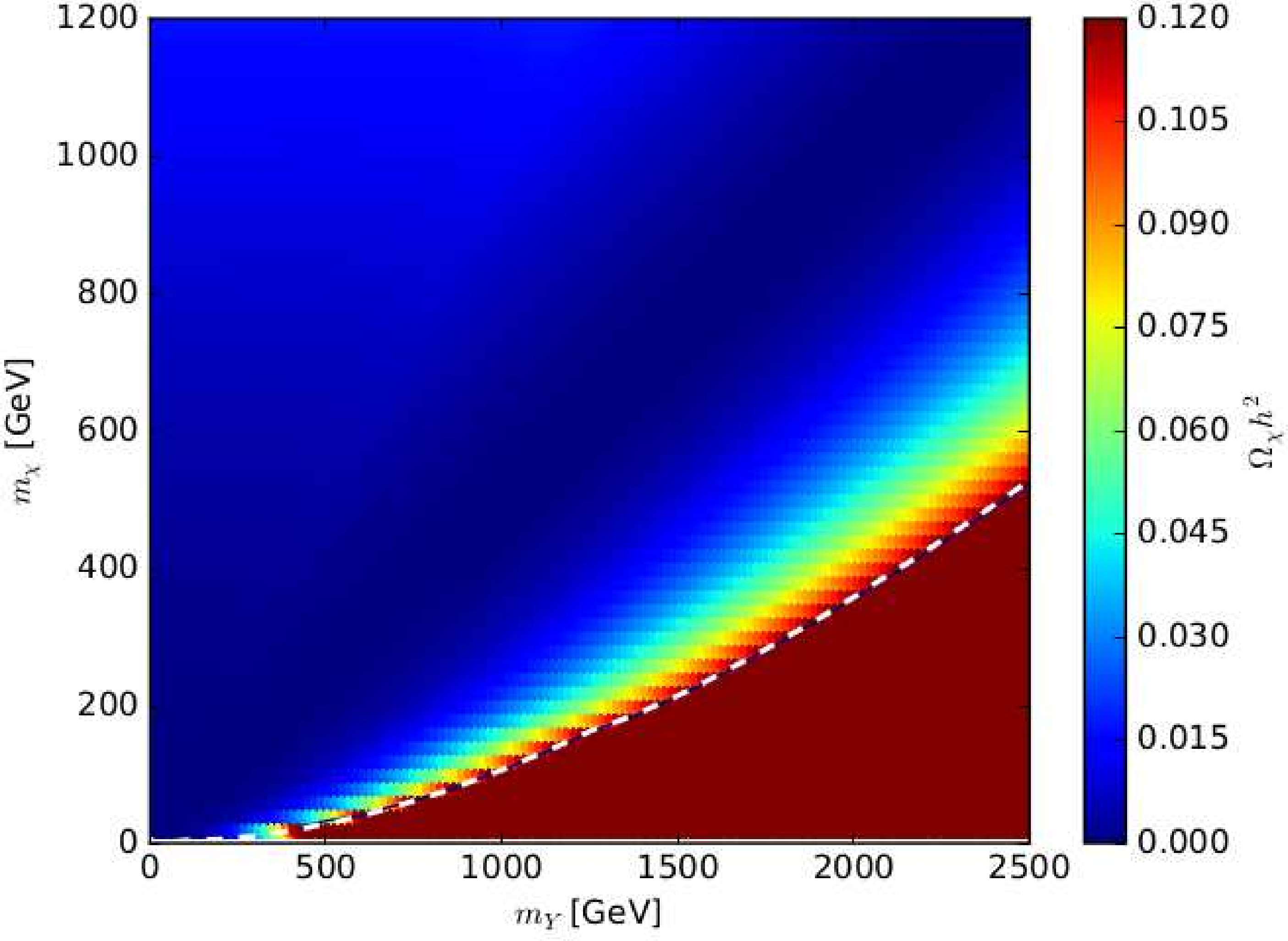
- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM, SU(5), mAMSB, sub-GUT
  - general models: pMSSM11, . . .
- Our tool: MasterCode: combination of LHC searches, Higgs measurements, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation
- Results wrt. neutrino floors:

Model	Min. χ^2/dof	χ^2-prob. (p)	$\sigma_p^{\rm SI}$	$\sigma_p^{\rm SD}$
CMSSM	32.8/18	11%	$2\,\sigma$	–
NUHM1	31.1/23	12%	$1\,\sigma$	–
NUHM2	30.3/22	11%	$1\,\sigma$	–
SU(5)	32.4/23	9%	$1\,\sigma$	–
mAMSB	36.5/27	11%	$2\,\sigma$	–
sub-GUT	28.9/24	23%	$3\,\sigma$	$1\,\sigma$ below
pMSSM11	22.1/20	33%	$3\,\sigma$	$1\,\sigma$ part. below

DM constraints:

[2019]

⇒ micrOMEGAs for relic density and DD cross sections

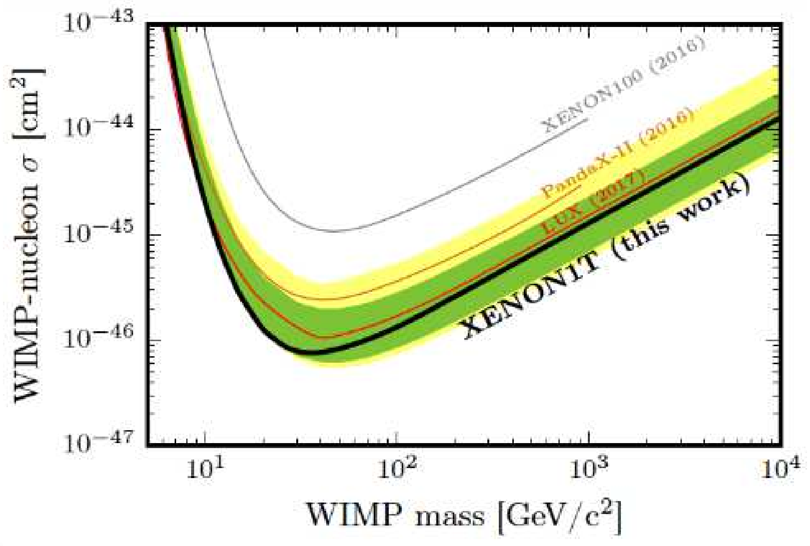


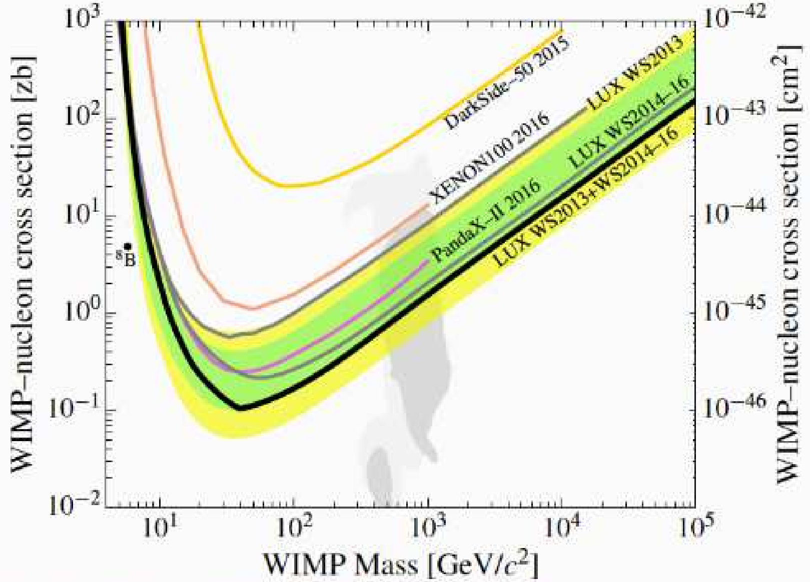
⇒ full agreement with ATLAS/CMS results (here: vector model)

Non-LHC constraints

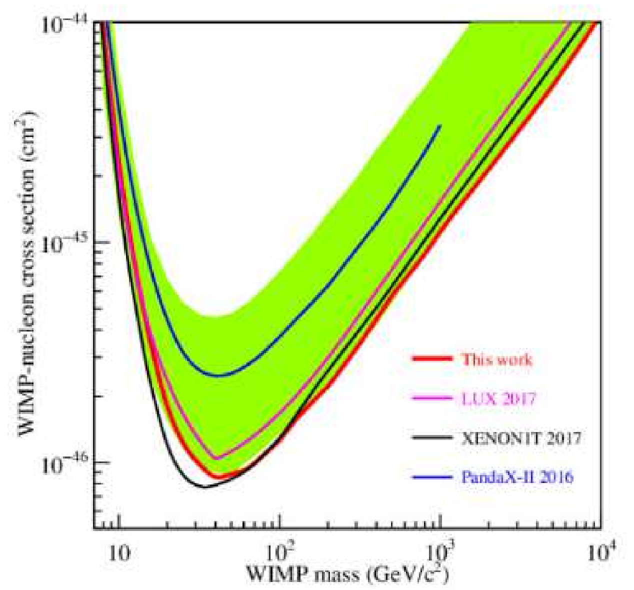
Dark matter

- Relic density constraints from Planck.
- Direct detection constraints on σ_p^{SI} from LUX, XENON1T and PANDAX.
- Direct detection constraints on σ_p^{SD} from PICO60.





[1608.07648, 1705.06655, 1708.06917]

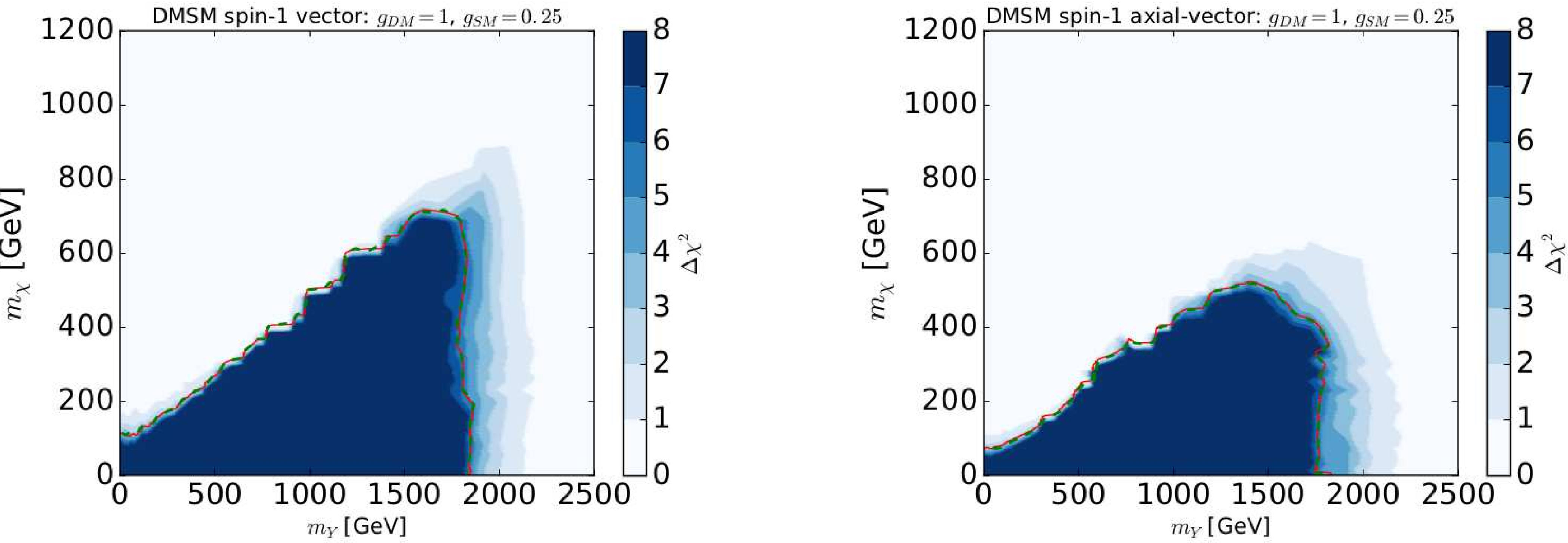


[*taken from E. Bagnaschi*]

Mono-jet constraints

[2019]

⇒ `MG5 aMC(N)LO`, `Fastlim` approach

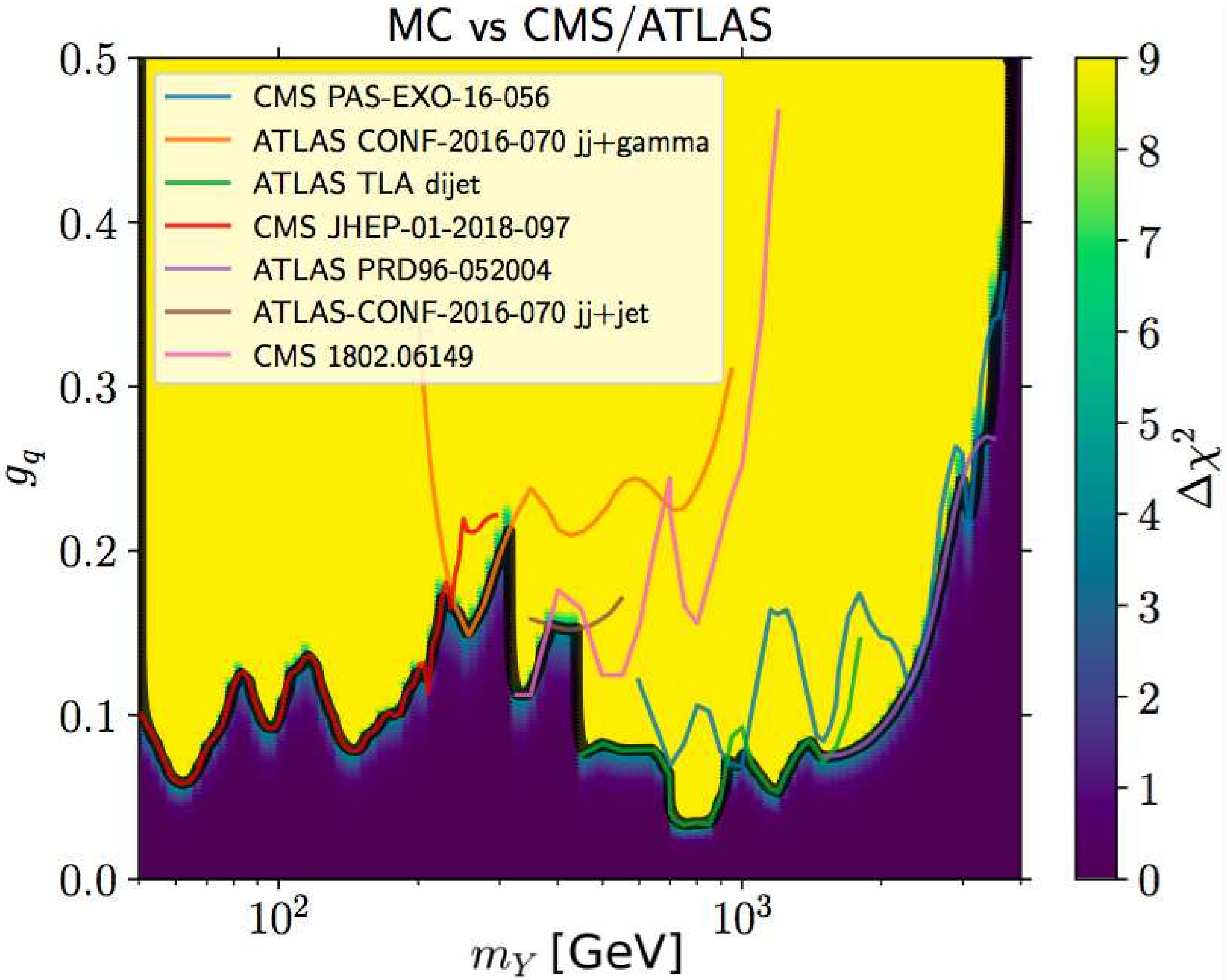


⇒ full agreement with ATLAS/CMS (red-dashed)

Di-jet constraints

[2019]

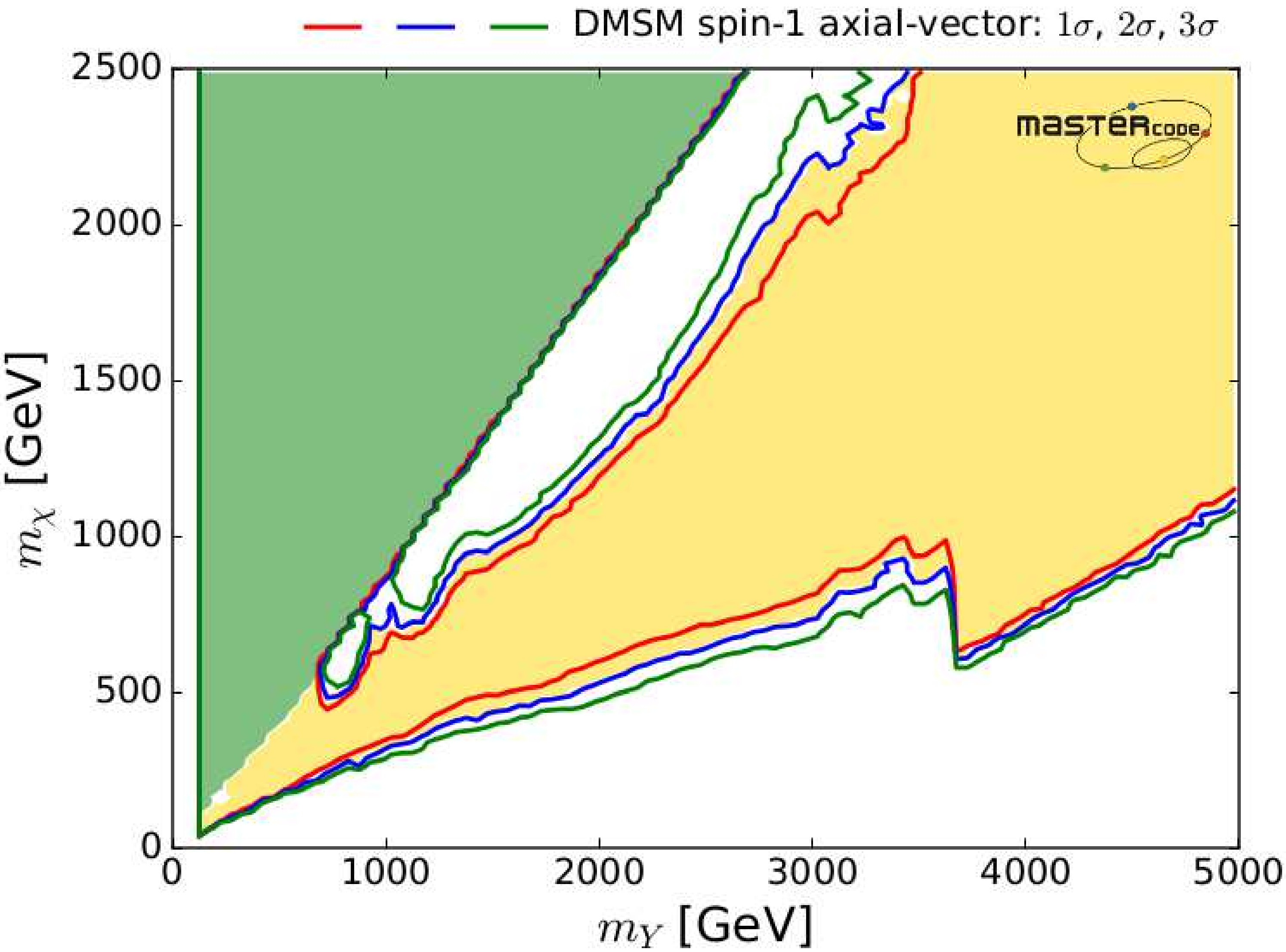
⇒ MG5 aMC(N)LO, Fastlim approach



⇒ full agreement with ATLAS/CMS

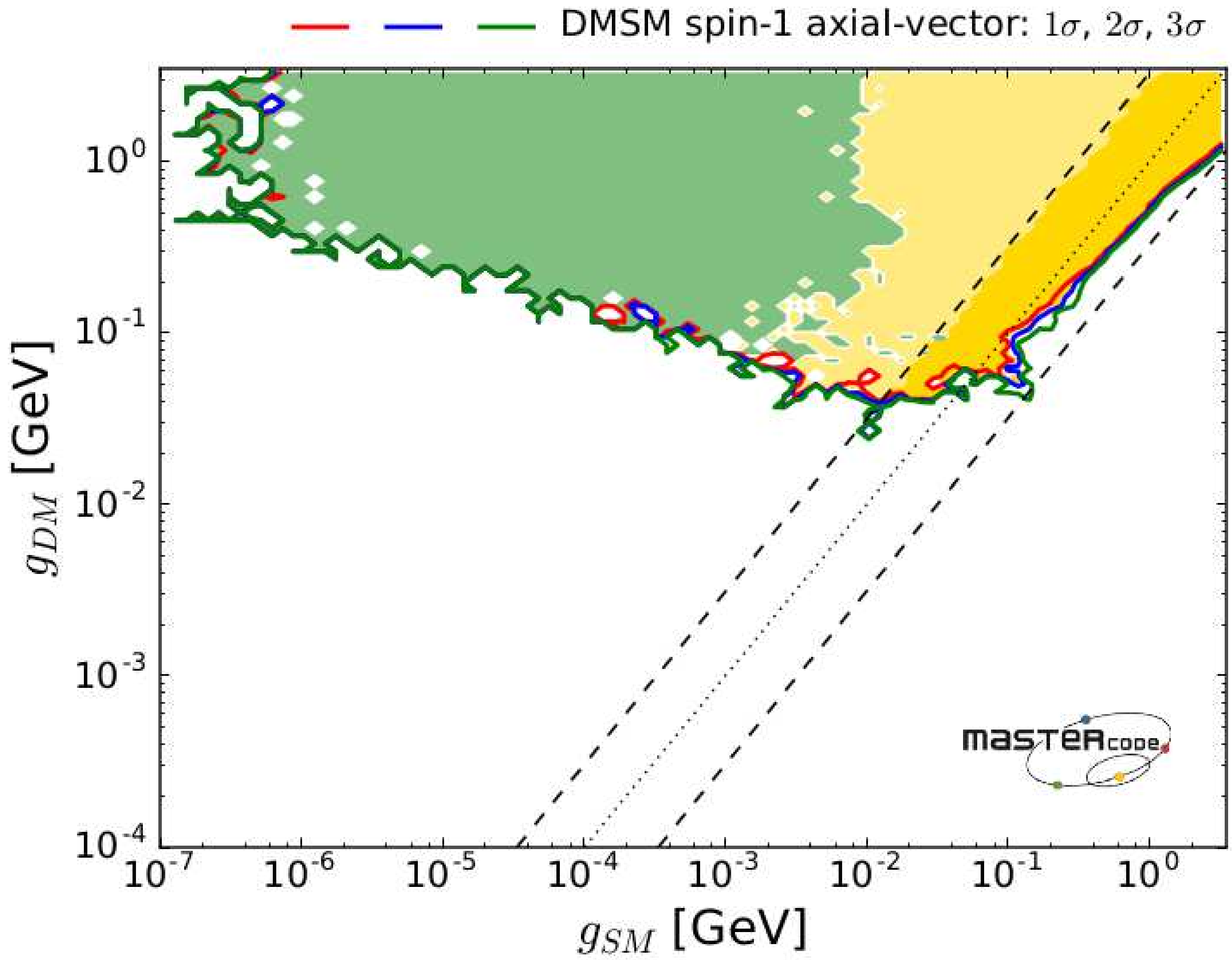
Axial-vector mediator (I):

[2019]



$\Rightarrow$ Larger s-channel region, continous with t-channel

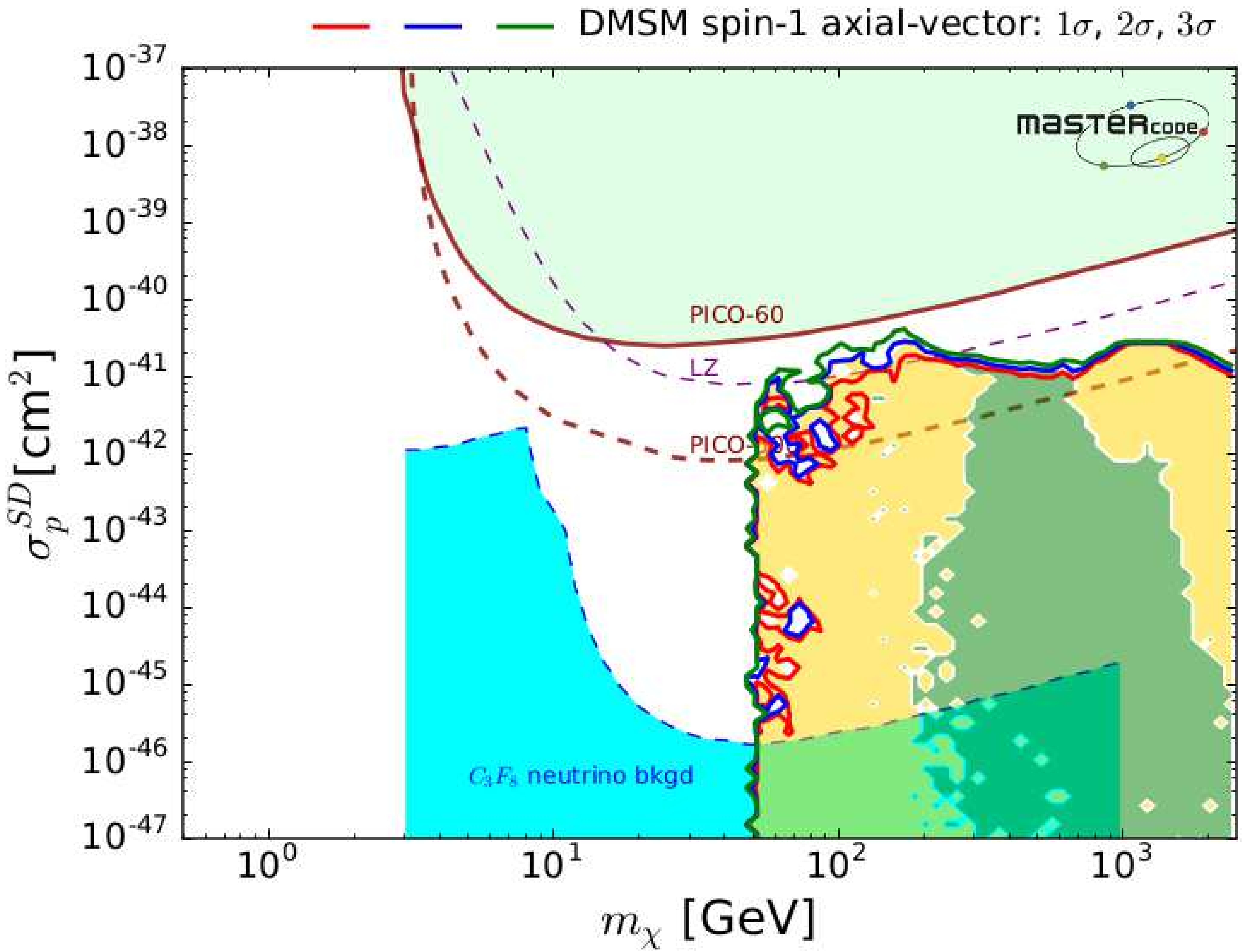
Axial-vector mediator (II): [2019]



$\Rightarrow$ t- (s-)channel for $g_{\mathrm{SM}} \lesssim (\gtrsim) 10^{-2}$

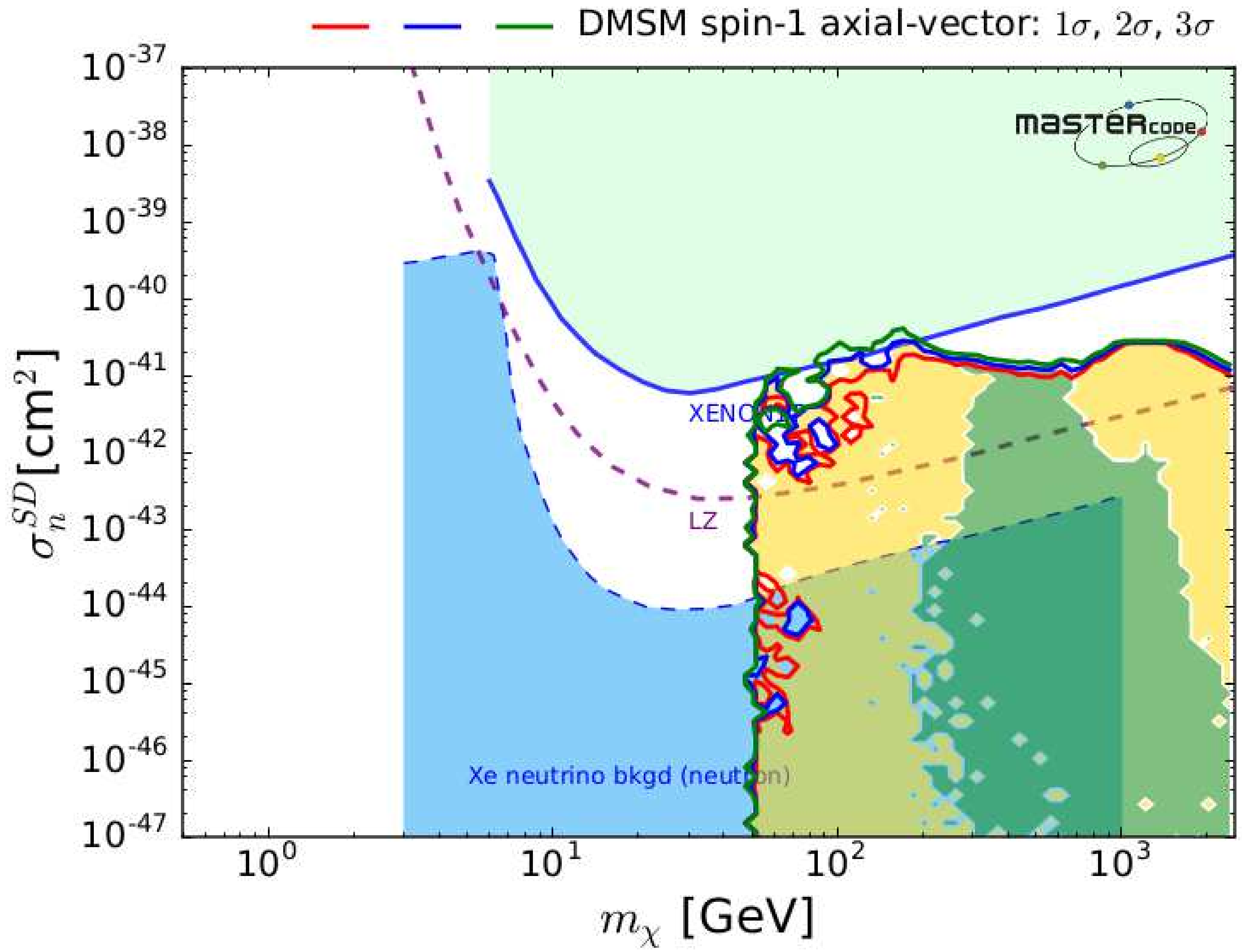
Axial-vector mediator (III):

[2019]



$\Rightarrow$ will not be easy for PICO!

Axial-vector mediator (III): [2019]



$\Rightarrow$ neither for LZ!